Tevatron Higgs Searches

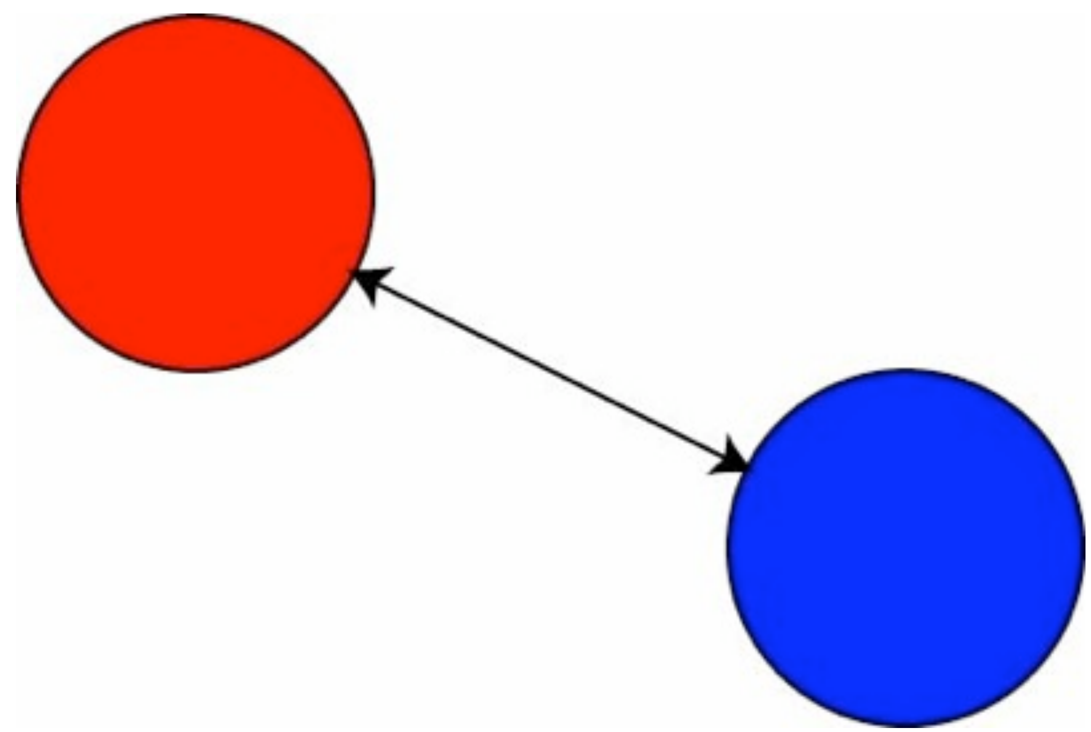
Aaron Dominguez, on behalf of D0 & CDF Collaborations

CIPANP 2009, San Diego

Partially supported by NSF grant PHY-0547780

Mystery of the "weak force"

- Gravity pulls two massive bodies (long-ranged)
- Electric force repels two like charges (long-ranged)
- "Weak force" pulls protons and electrons (short-ranged) acts only over 10^{-16} cm
- (This is probably well known to the nuclear and particle physicists in the crowd)

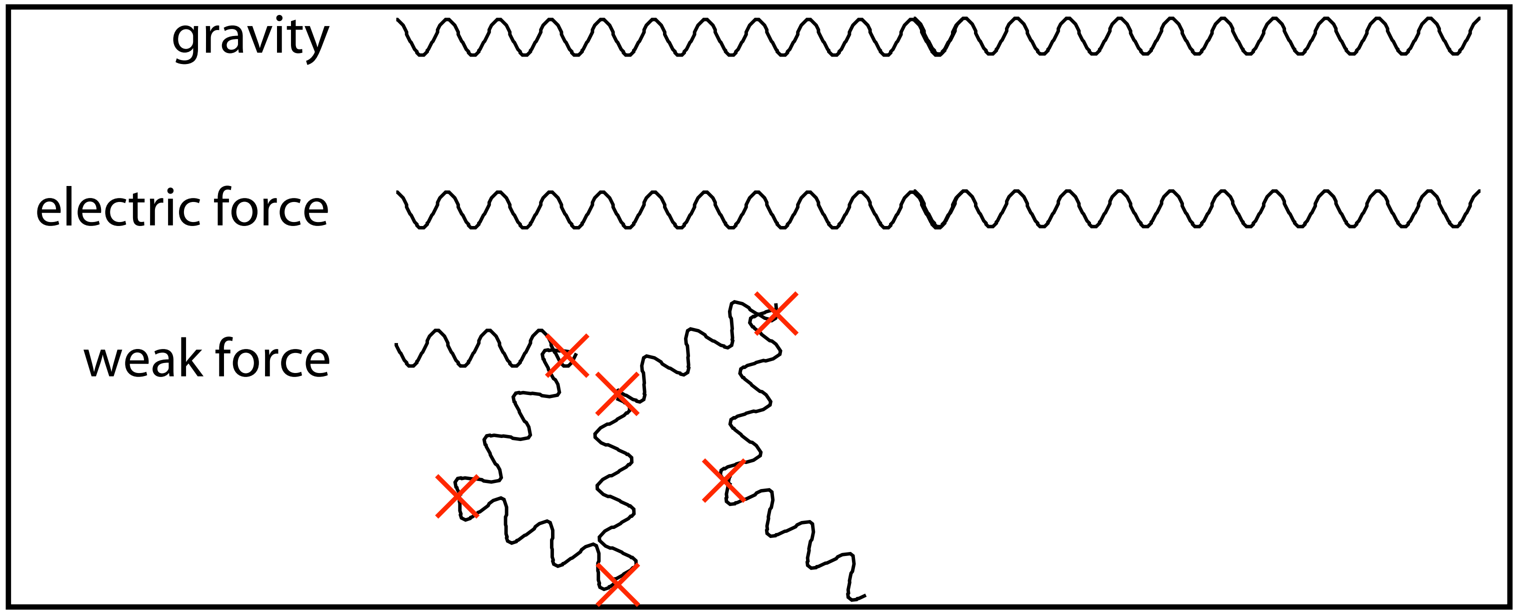


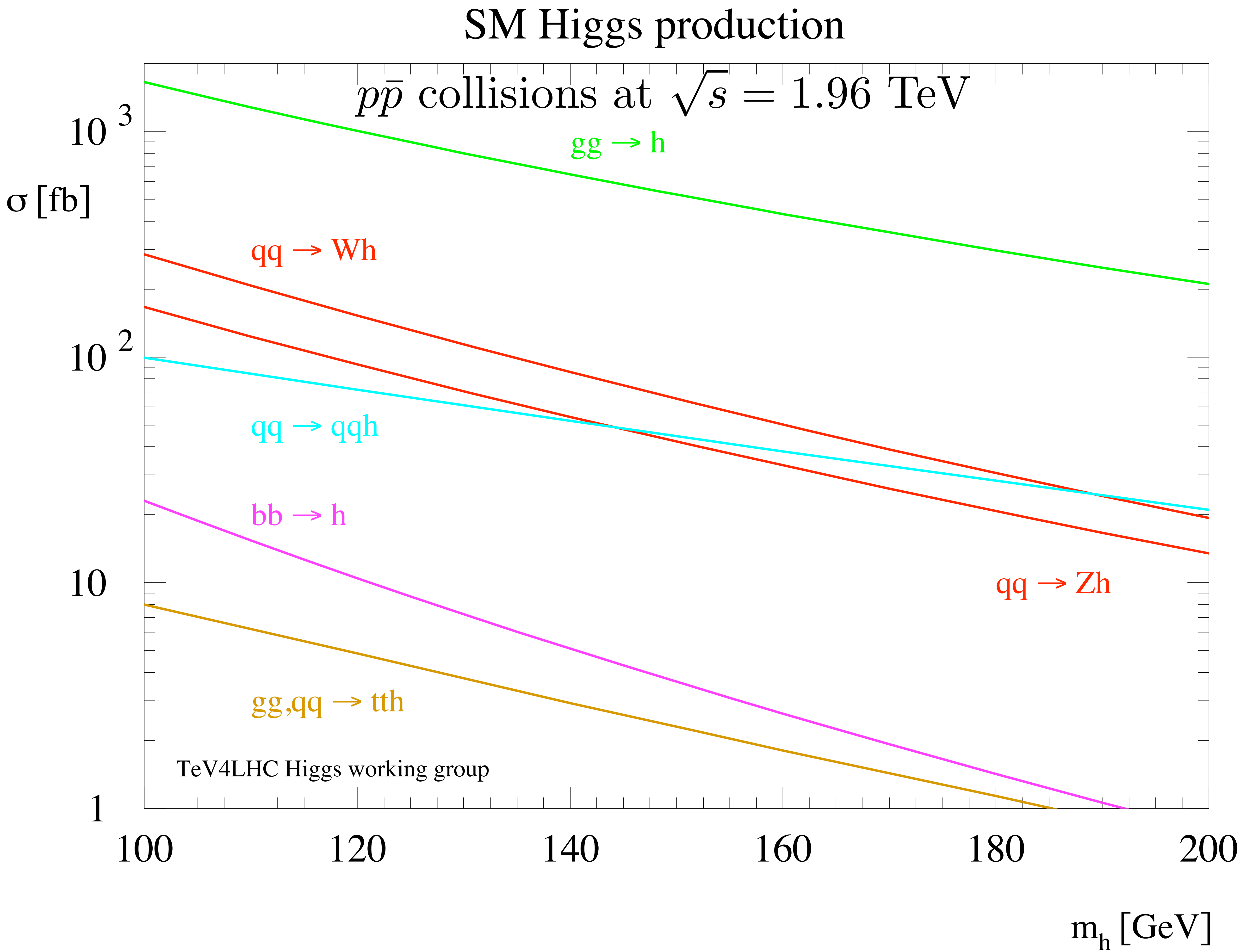
Something's Missing...

- Generations of matter different in mass
- Why do they have different masses?
- Why is the weak force "weak?" Because m_W, $m_Z > 0$.
- OK, so why are m_W, $m_Z > 0$?
- One "solution" is a new particle: Higgs boson

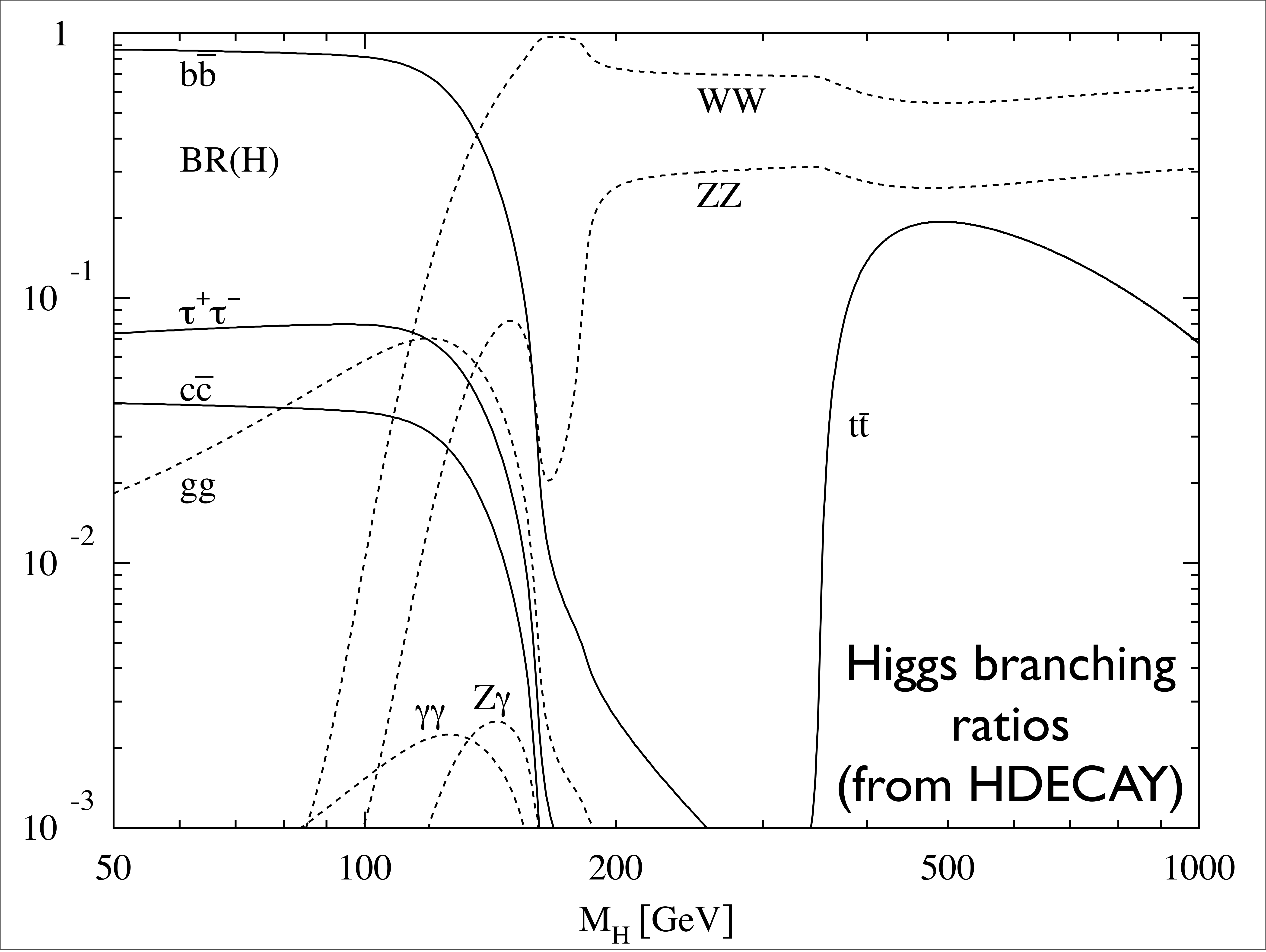
Higgs Field

- According to this model, the Higgs field fills the universe
- It doesn't disturb gravity, strong or the EM force
- It does disturb the weak force and makes it short ranged
- In the simplest model, the physical Higgs particle could be giving mass to the fermions

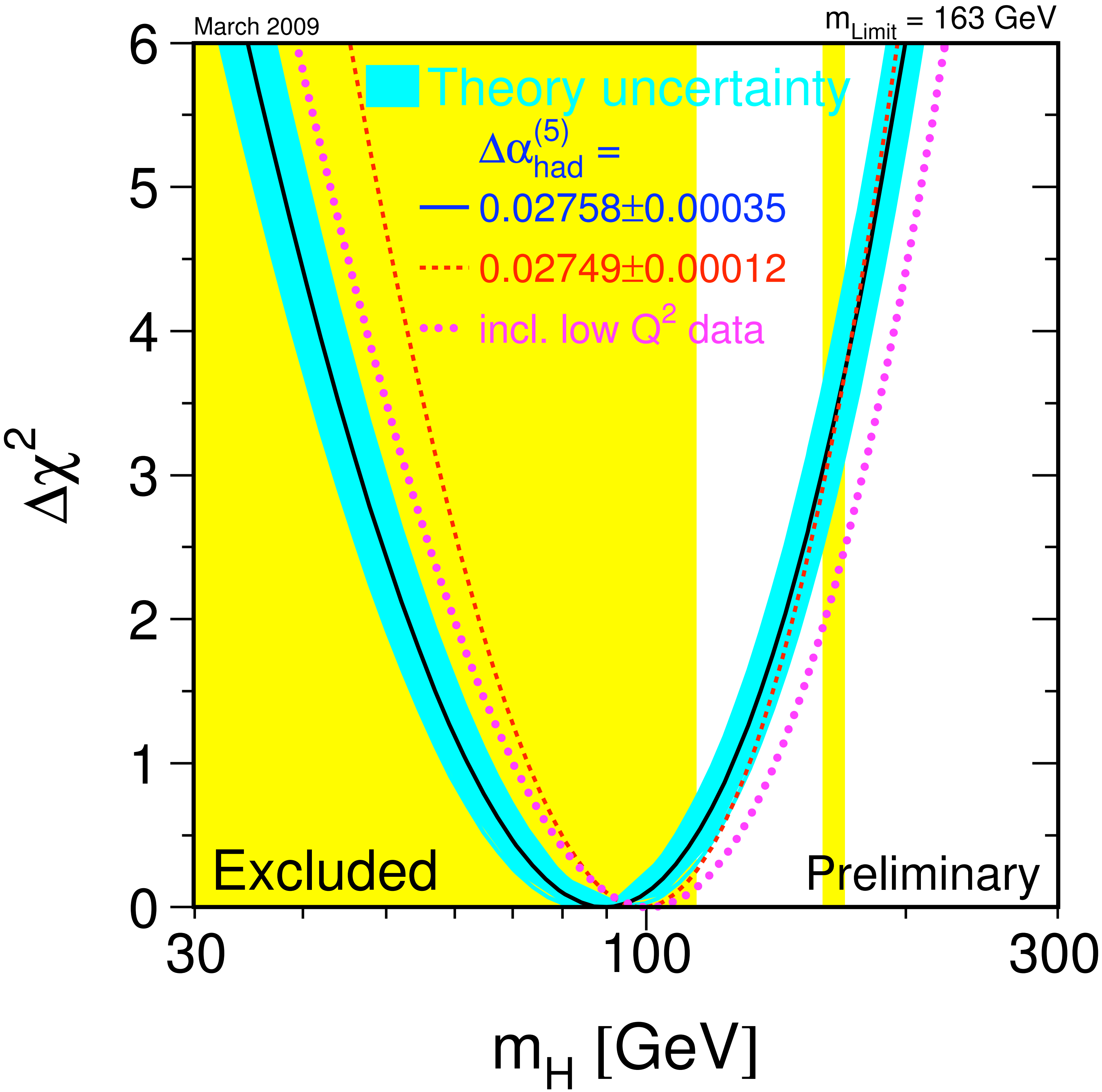




SM Higgs production
$p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV
$gg \to h$
$qq \to Wh$
$qq \to qqh$
$bb \to h$
$qq \to Zh$
$gg,qq \to tth$
TeV4LHC Higgs working group
σ [fb]
m_h [GeV]
10^3
10^2
10
1
100
120
140
160
180
200


1
10^-1
10^-2
10^-3
bb̄
BR(H)
WW
ZZ
τ+τ−
cc̄
gg
tt̄
γγ
Zγ
Higgs branching
ratios
(from HDECAY)
50
100
200
500
1000
M_H [GeV]

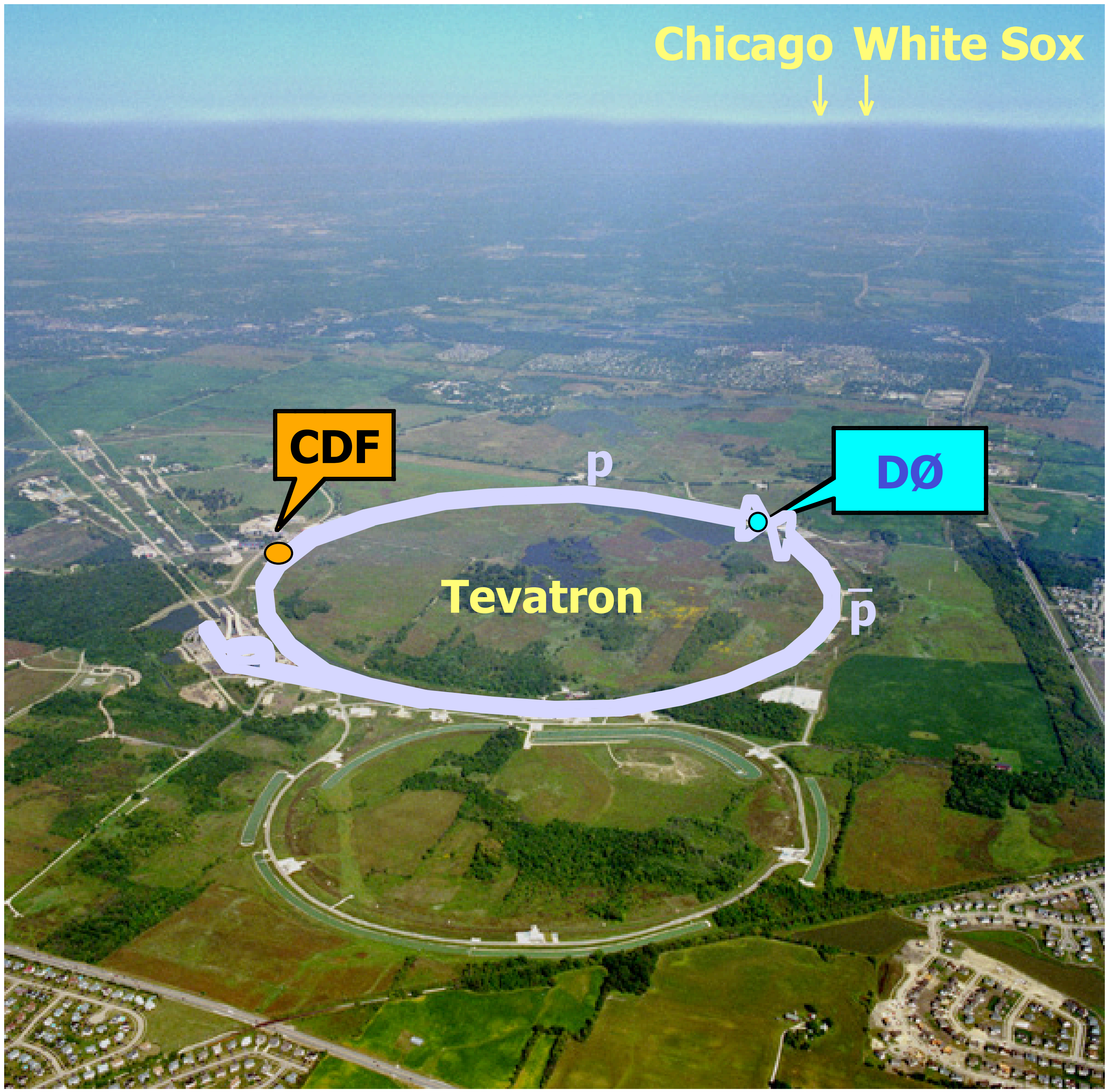
What have we learned?



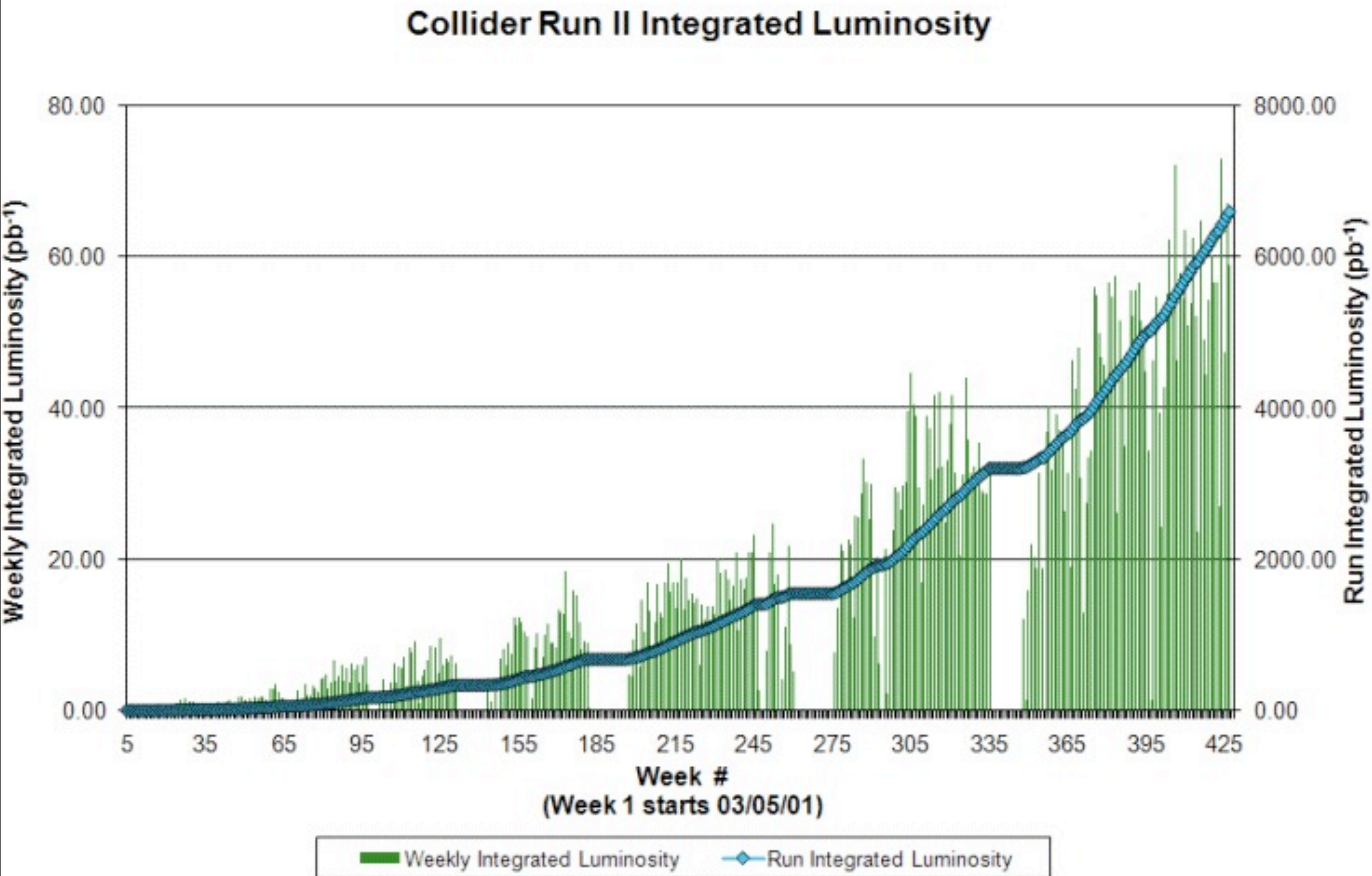
(LEP EW Working Group)

- Direct searches from LEP limit SM Higgs to be m_H>114 GeV (95% CL)
- Fits to EW data limit it to m_H<191 GeV
- Tevatron has now made direct search limits on the SM Higgs too, as we shall see...

DZERO, CDF & Run II

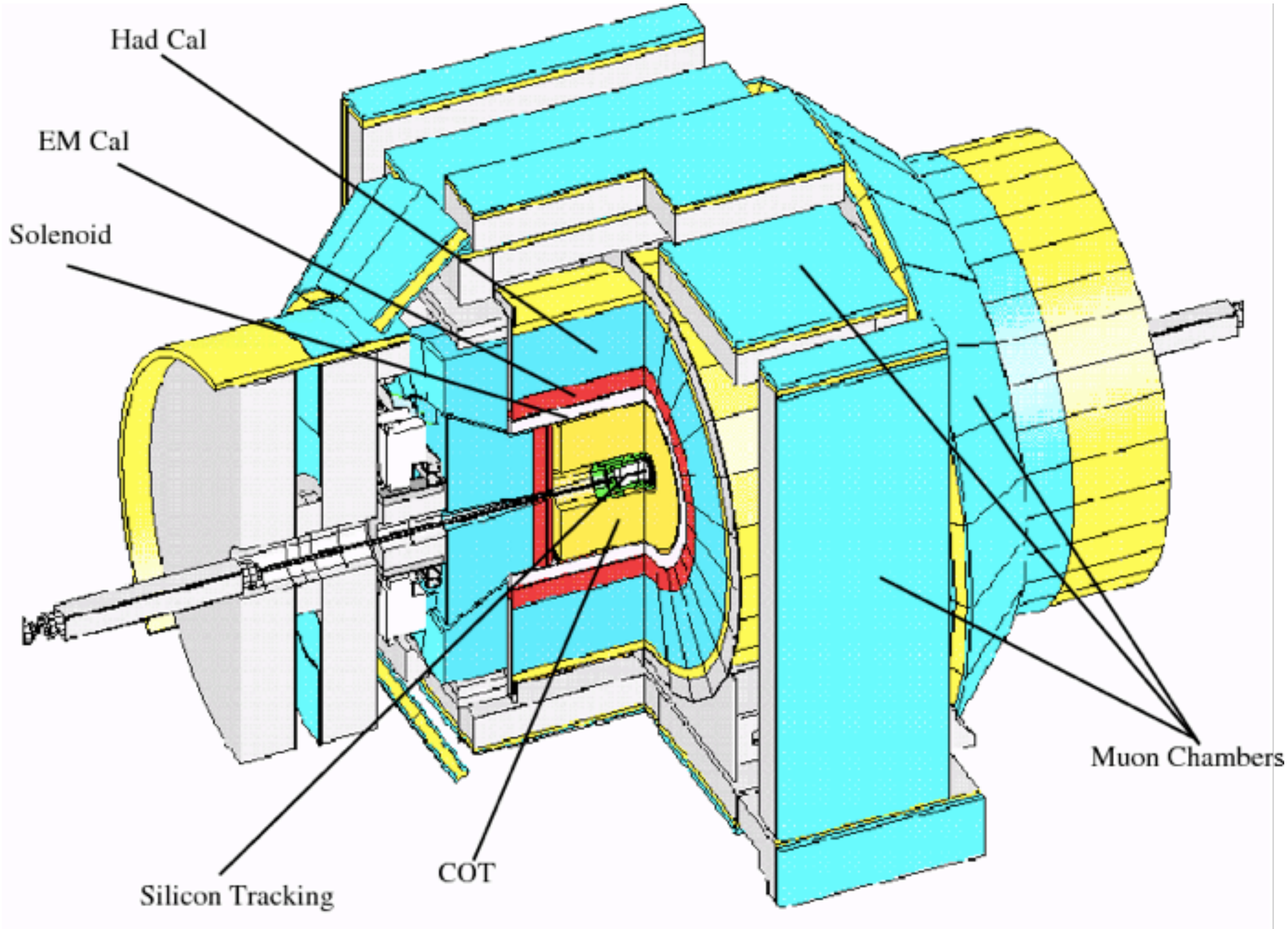


- Started in 2001
- $p\bar{p}$ collider
- $\sqrt{s} = 1.96$ TeV
- $\int \mathcal{L} \sim 6 \text{ pb}^{-1}$
- Will get $\int \mathcal{L} \sim 9 \text{ pb}^{-1}$
- Multipurpose detectors



Collider Run II Integrated Luminosity
80.00
60.00
40.00
20.00
0.00
8000.00
6000.00
4000.00
2000.00
0.00
Weekly Integrated Luminosity (pb-1)
Run Integrated Luminosity (pb-1)
5 35 65 95 125 155 185 215 245 275 305 335 365 395 425
Week #
(Week 1 starts 03/05/01)
Weekly Integrated Luminosity
Run Integrated Luminosity

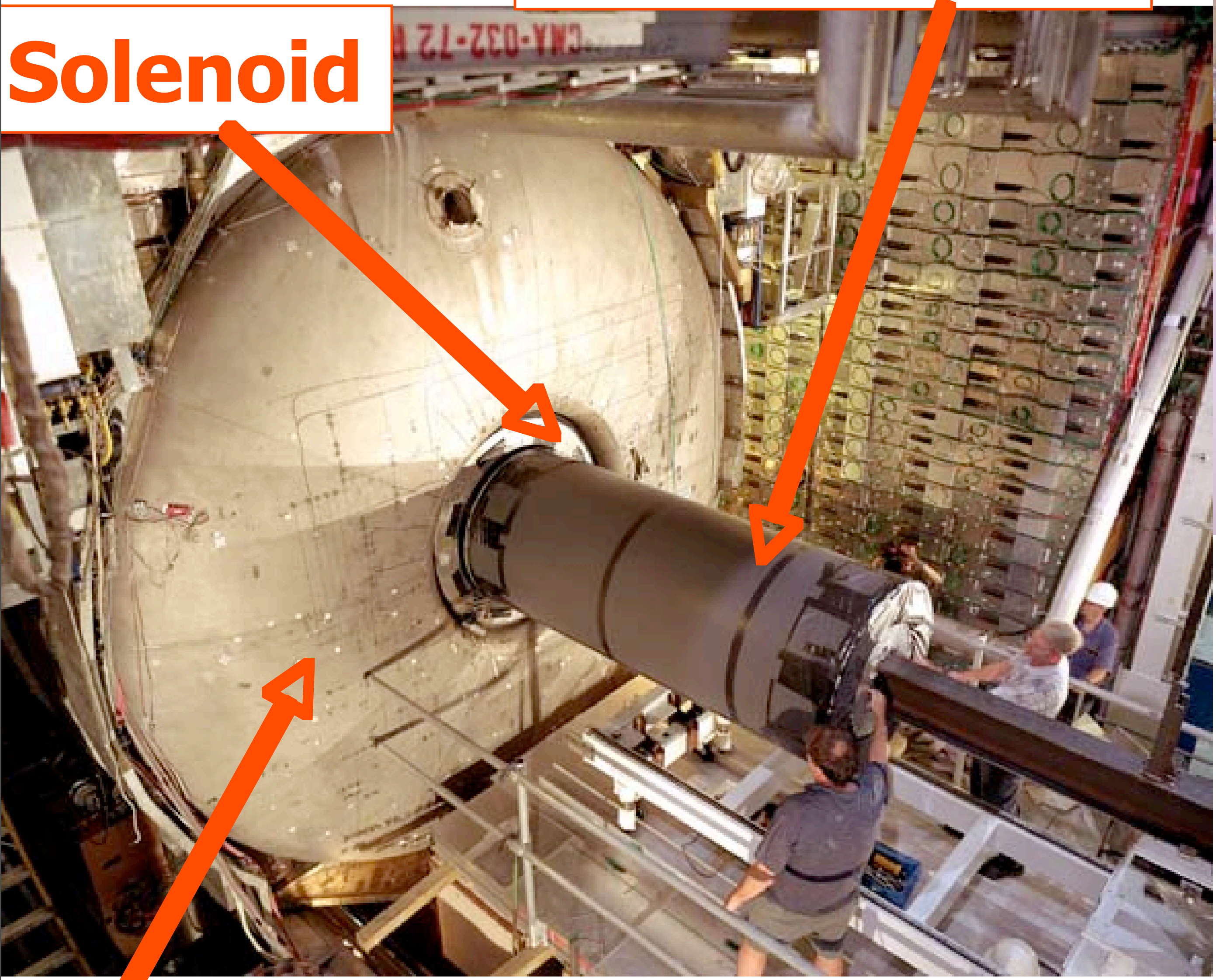
CDF

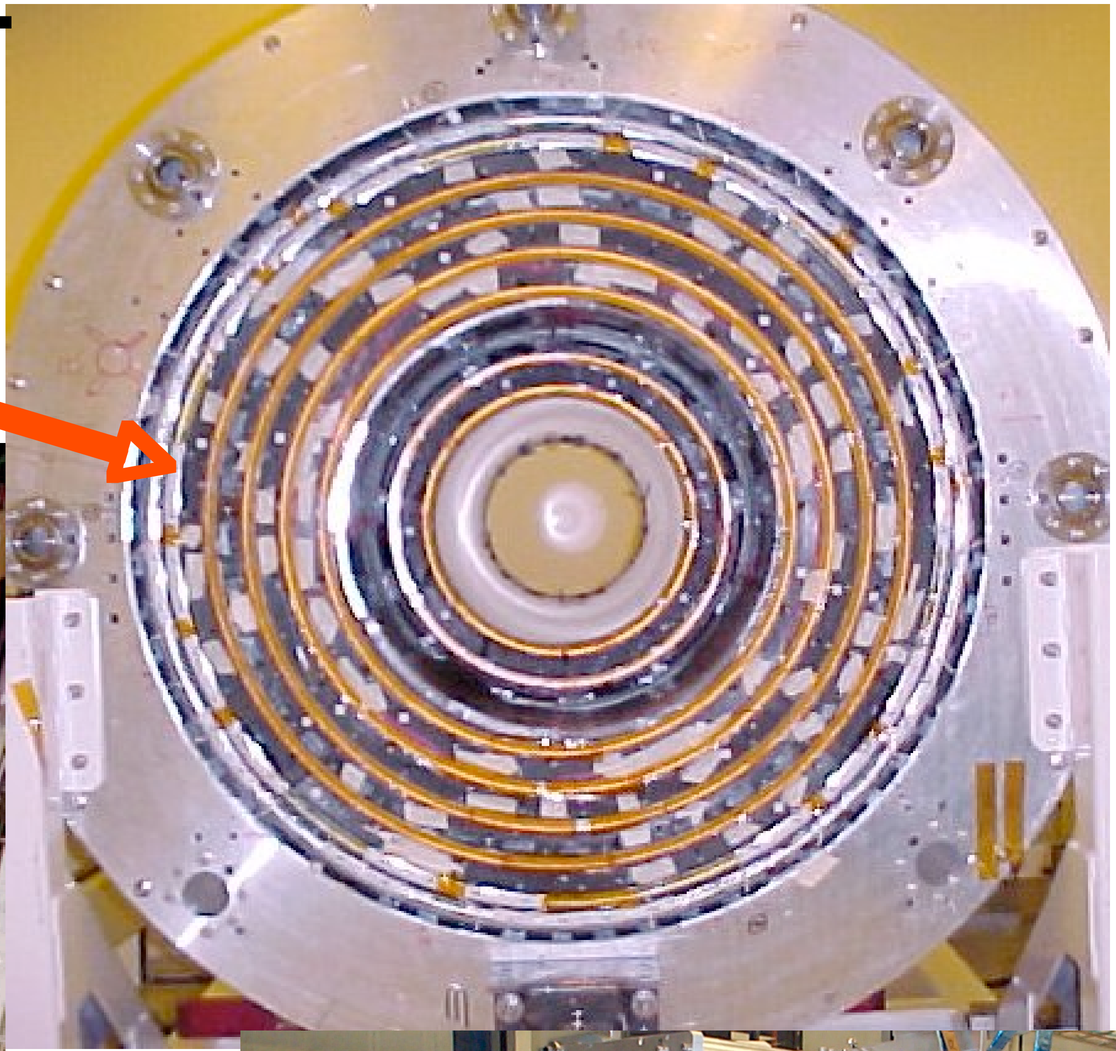


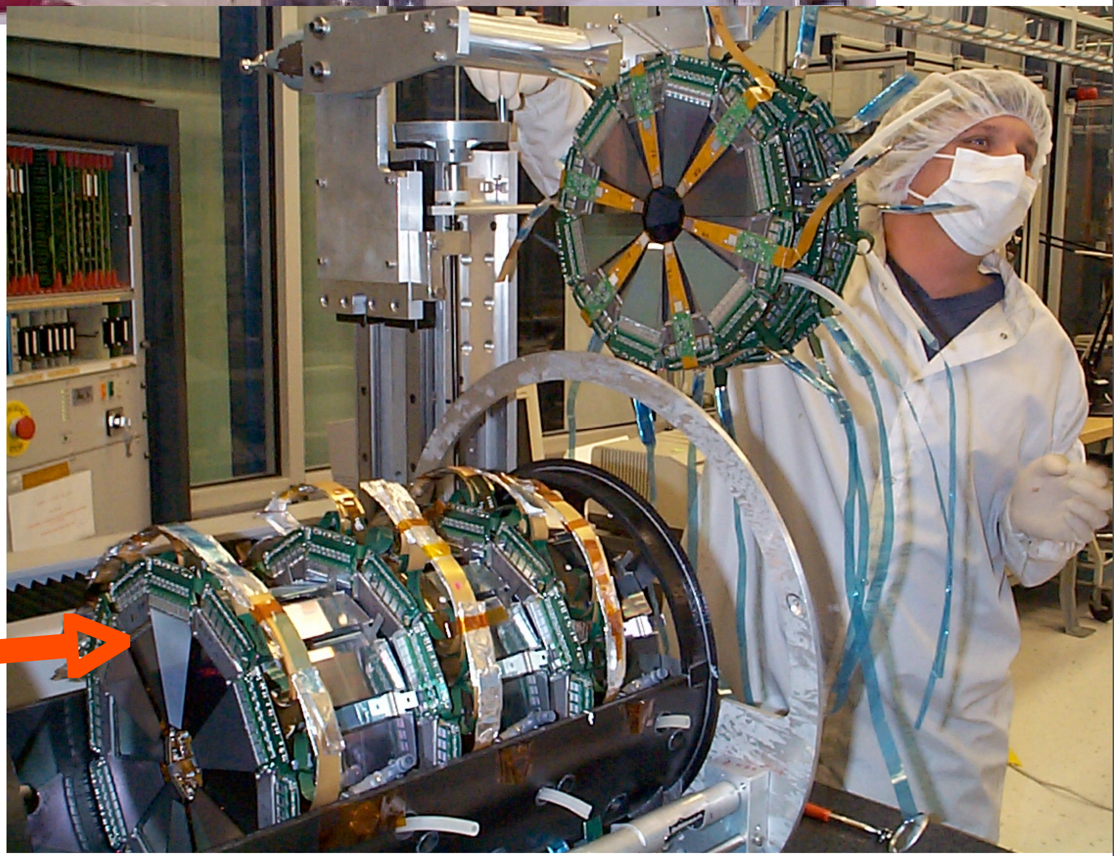
- Silicon vertex inner tracker
- Wire chamber outer tracker
- Pb-scintillator ECAL
- Fe-scintillator HCAL
- Muon chambers up to $|\eta|<1.5$

Muon coverage to $|\eta|<2.2$

DØ Detector



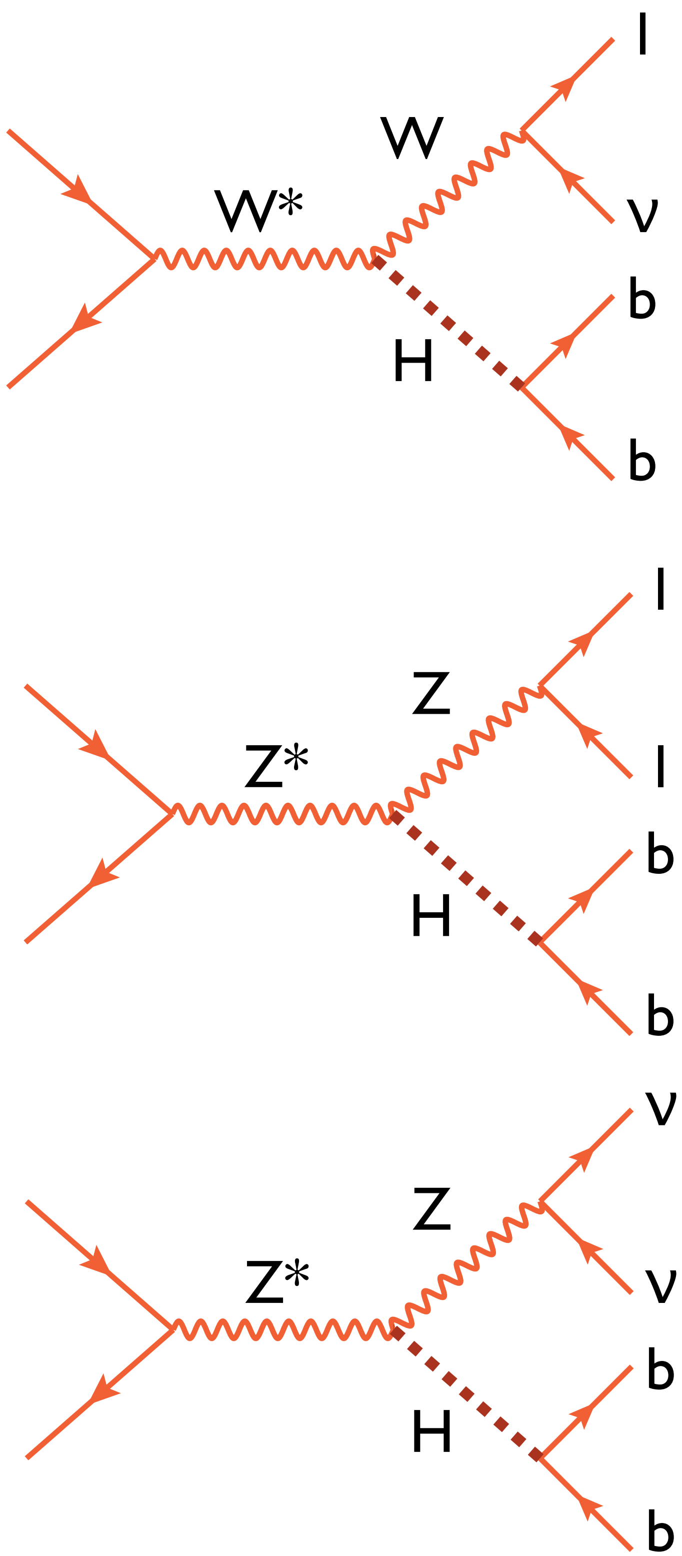




Search Strategy

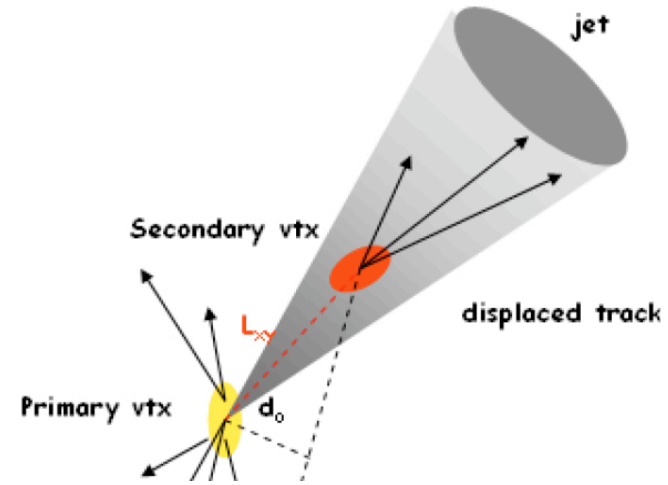
- On slides 5 and 6, we saw the predicted production and decay modes of the SM Higgs. These set the stage for our approach.
- Both CDF & D0 are good at triggering on leptons in the final state
- Hadronic final state searches are also possible, but usually offer more challenging backgrounds from pure QCD interactions
- Since m_H is unknown, we do our best to cover all possible production/decay modes

"Low Mass" Searches

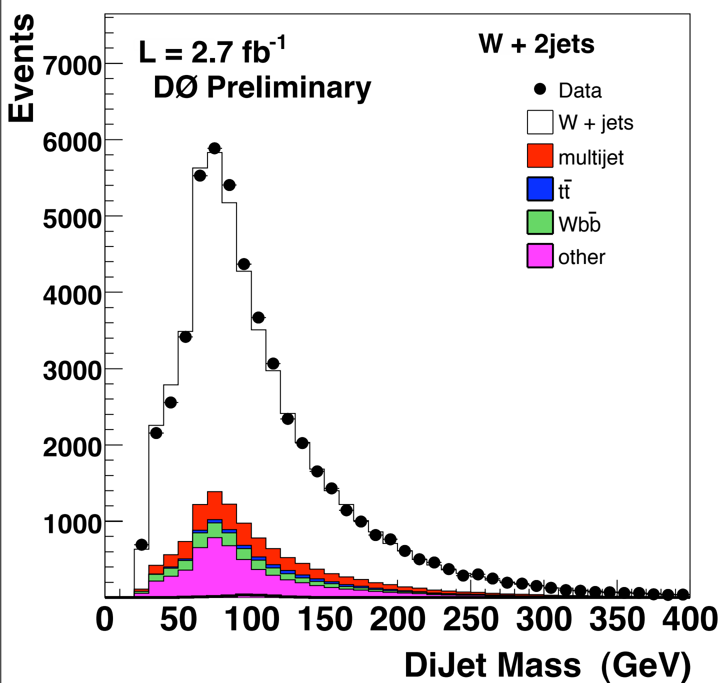


- In mass region where $H \to b\bar{b}$ dominates, we look in production modes where the Higgs is made in association with a massive vector boson, which gives leptons in the final state to trigger on.
- Higgs decays into b quarks, taus and (via a loop) photons. We use all of these.
- The gluon fusion production mode is about 5 times bigger, but the QCD background is 10^6 times bigger, so we haven't figured out how to use this channel.

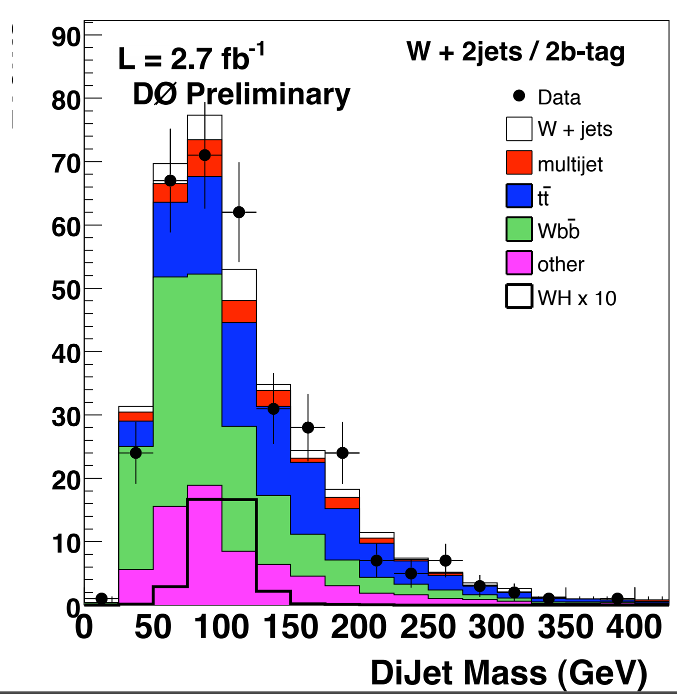
B-Tagging



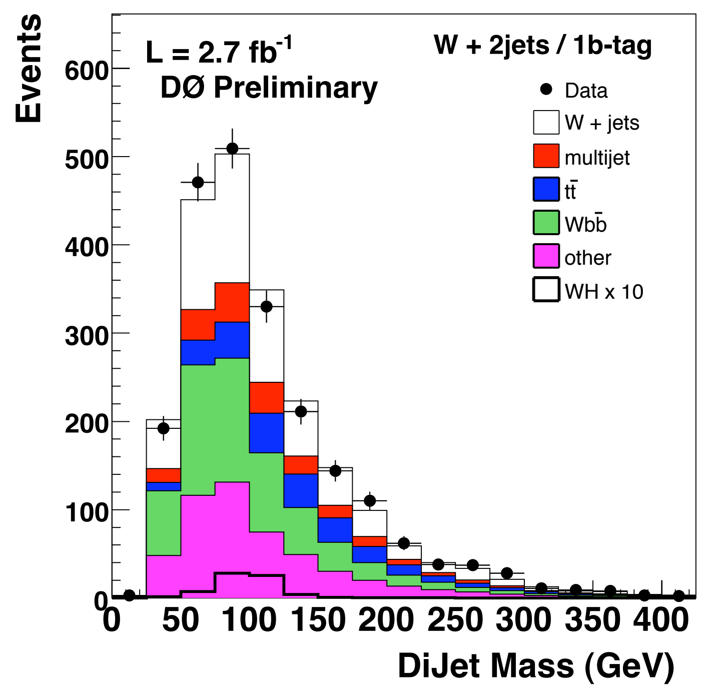
S:B ~ 1:3000



S:B ~ 1:100



S:B ~ 1:300

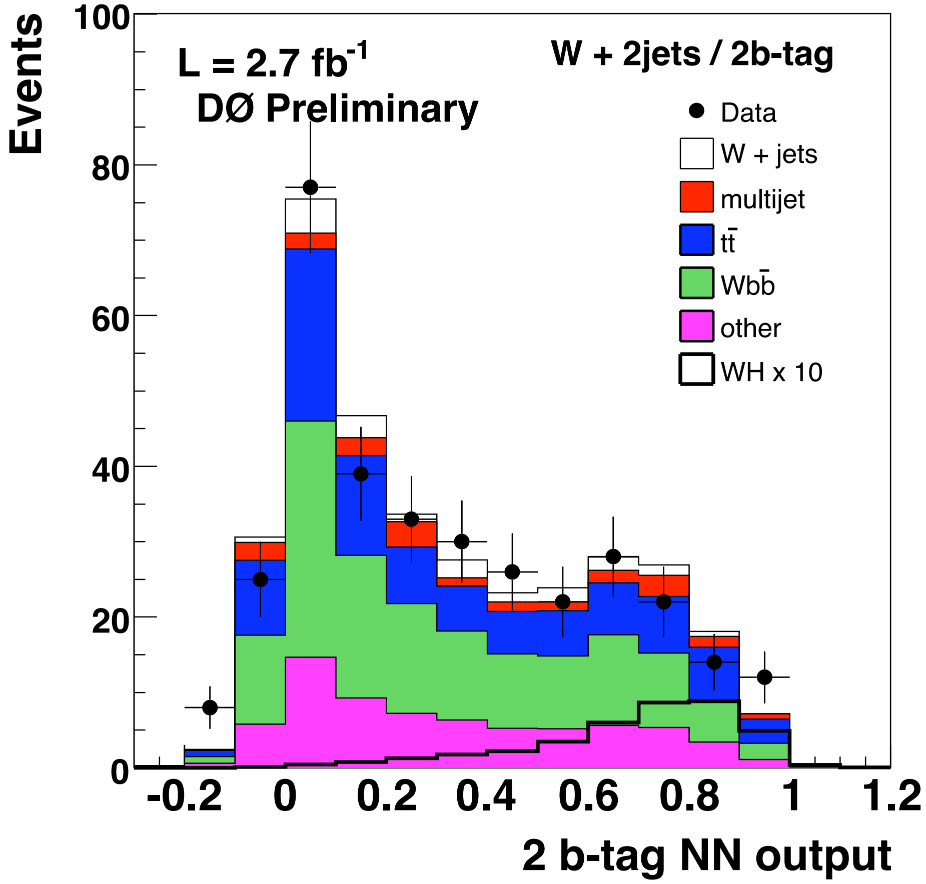


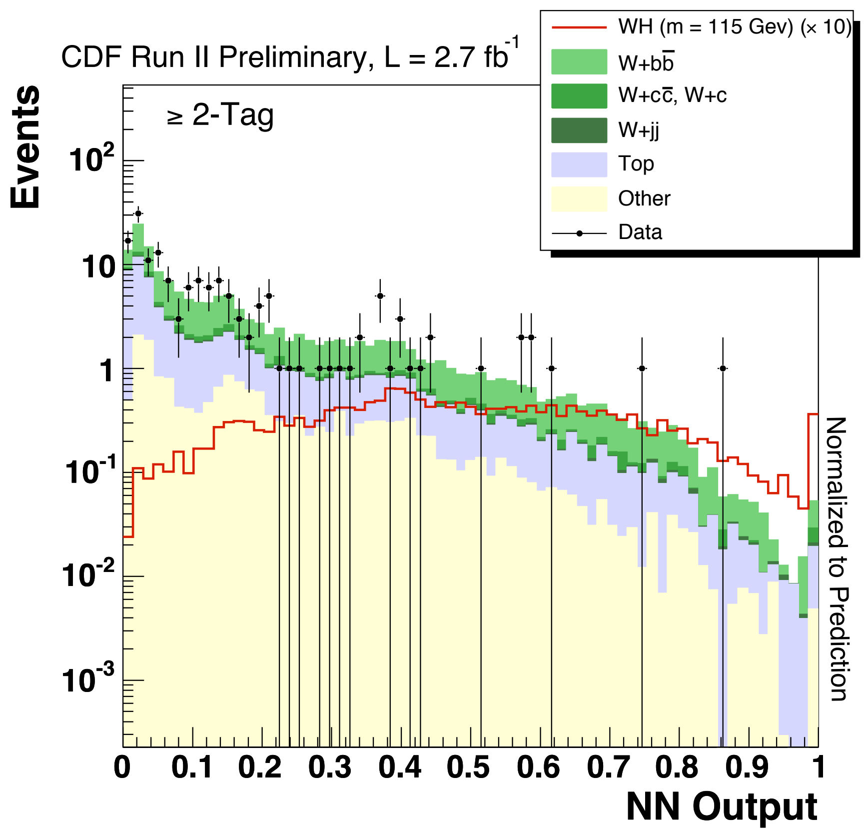
- Identifying b-jets vastly improves signal sensitivity in H to bb channels
- CDF uses a 2nd vertex tag and a jet probability built from the CL that all tracks in the jet are consistent with the primary vtx
- D0 uses a neural network with inputs from vtx info, impact pars and jet info

$WH \to \ell\nu b\bar{b}$

- High pT charged lepton (usually triggered on), missing energy, and b-tags
  - CDF: pT > 20 GeV; $|\eta_e|<2$; $|\eta_\mu|<1$; MET > 20 GeV; 2 jets > 20 GeV; $|\eta_{jet}|<2$; 1 or 2 b-tags
  - D0: pT > 15 GeV; $|\eta_e|<2.5$; $|\eta_\mu|<2$; MET > 20 GeV; 2 or 3 jets > 25 or 20 GeV; $|\eta_{jet}|<2.5$; 1 or 2 b-tags
- Backgrounds: W with jets; multijets; top

$WH \rightarrow \ell\nu bb$



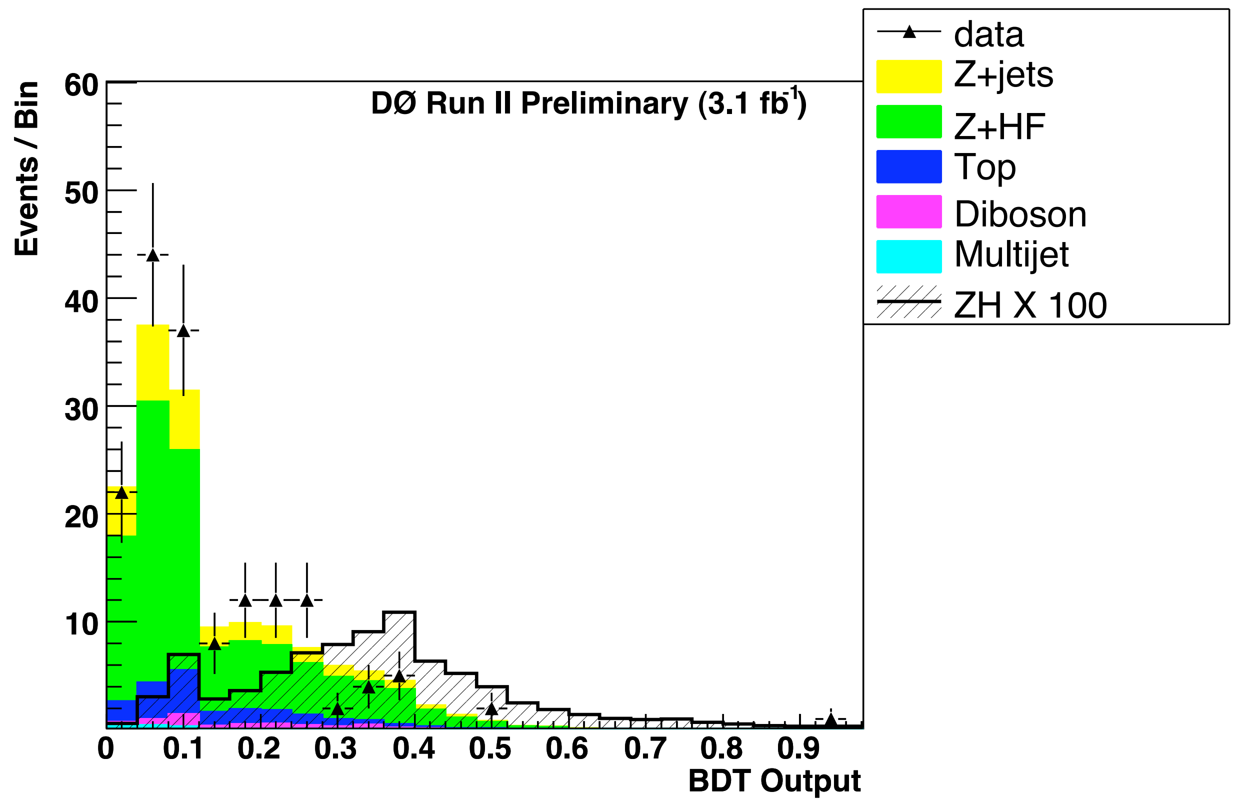


- D0 uses neural network
- D0 expects 6.4 x SM cross section and observes 6.7 x SM for m_H=115 hypothesis
- CDF uses a neural network to combine boosted decision tree, matrix element & NN
- CDF expects 4.8 x SM cross section, observes 5.6 x SM.

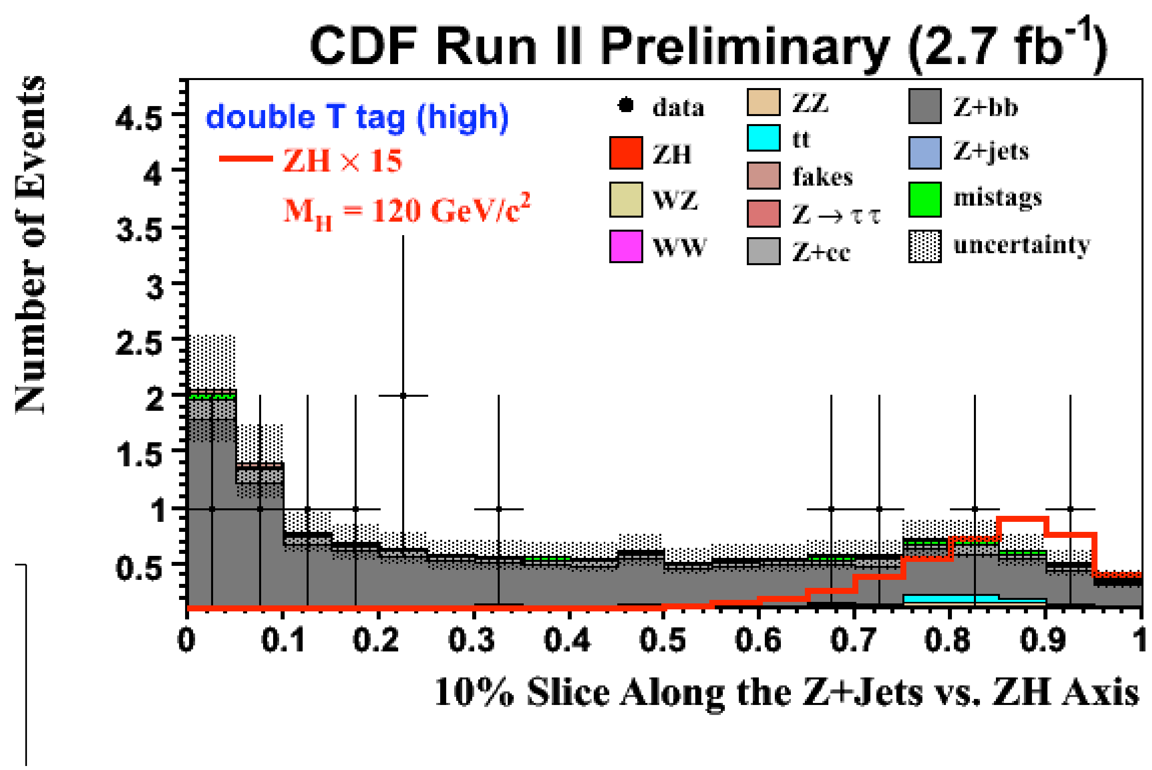
$ZH \to \ell^+ \ell^- b\bar{b}$

- 2 High pT charged leptons, 2 or more jets, and b-tags
  - CDF: pT > 18 GeV; $|\eta_e|<2.8$; $|\eta_\mu|<2.0$; 2+ jets > 25, 15 GeV; $|\eta_{jet}|<2$; b-tags create 6 different $S/\sqrt{B}$ samples
  - D0: pT > 10 GeV; $|\eta_e|<2.5$; $|\eta_\mu|<2$; 2+jets > 20, 15 GeV; $|\eta_{jet}|<2.5$; 1 tight or 2 loose b-tags
- Backgrounds: Z with jets; multijets; top

$ZH \to \ell^+\ell^- b\bar{b}$



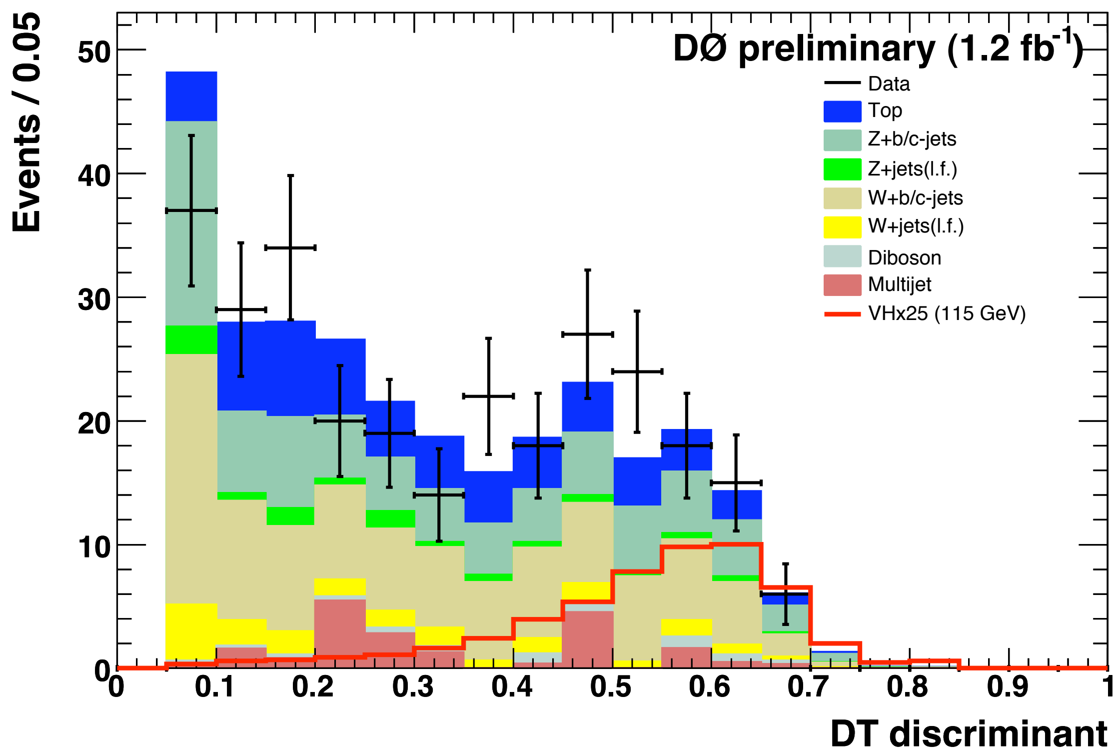
- D0 uses boosted decision trees in both channels
- D0 expects 8.0 x SM cross section, observes 9.1 x SM for m_H=115 GeV hypothesis
- CDF uses neural network against Zbb & top
- CDF sees no excess in 6 different b-tag samples, sets a limit on the cross section of 9.9 x SM expected and 7.1 x SM observed

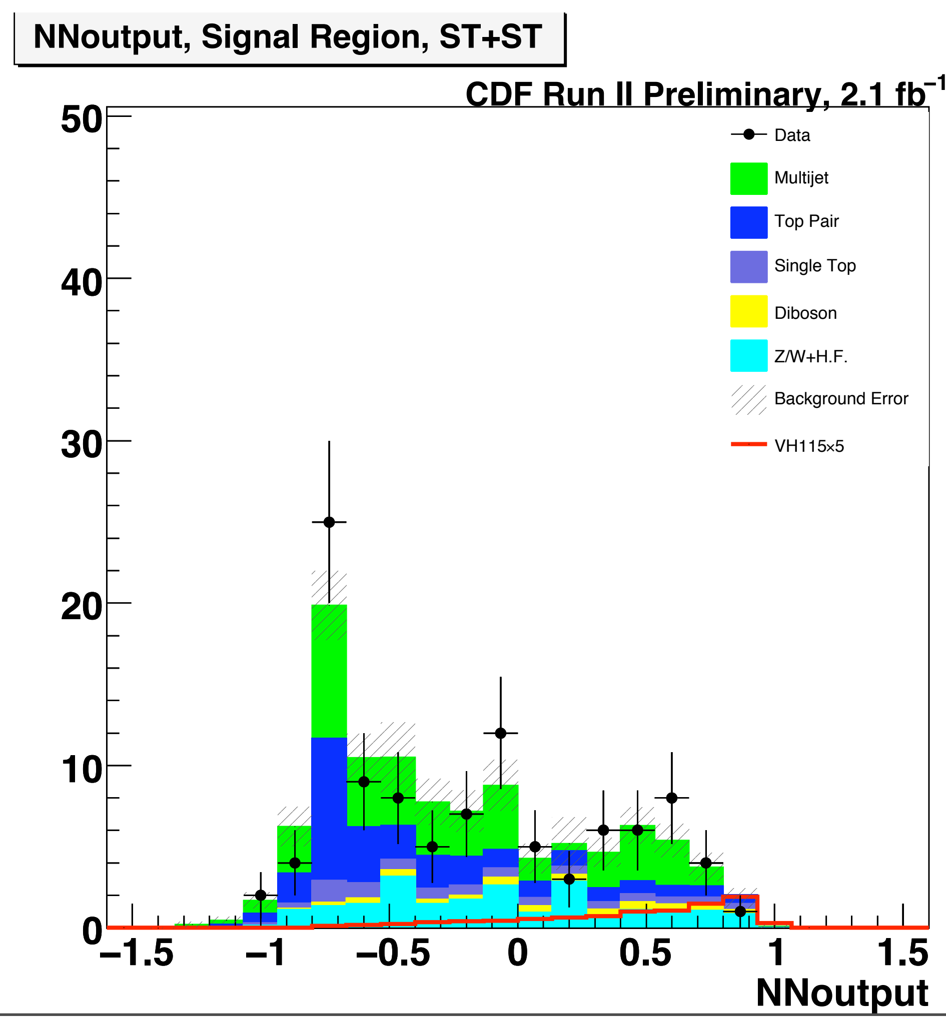


$ZH \rightarrow \nu\bar{\nu}b\bar{b}$

- This analysis also accepts a good fraction of the $WH \rightarrow \ell\nu b\bar{b}$ channel where the lepton is missing.
- The signature is 2 high pT b-jets and large missing energy from the neutrinos
  - CDF: MET > 50 GeV; 2+ jets > 35, 20 GeV; $|\eta_{jet}|<2.0$; b-tags similar to WH
  - D0: MET > 50 GeV; 2+ jets > 20 GeV; $\Delta\phi_{jets}<165^{\circ}$; $|\eta_{jet}|<2.5$; b-tags like WH

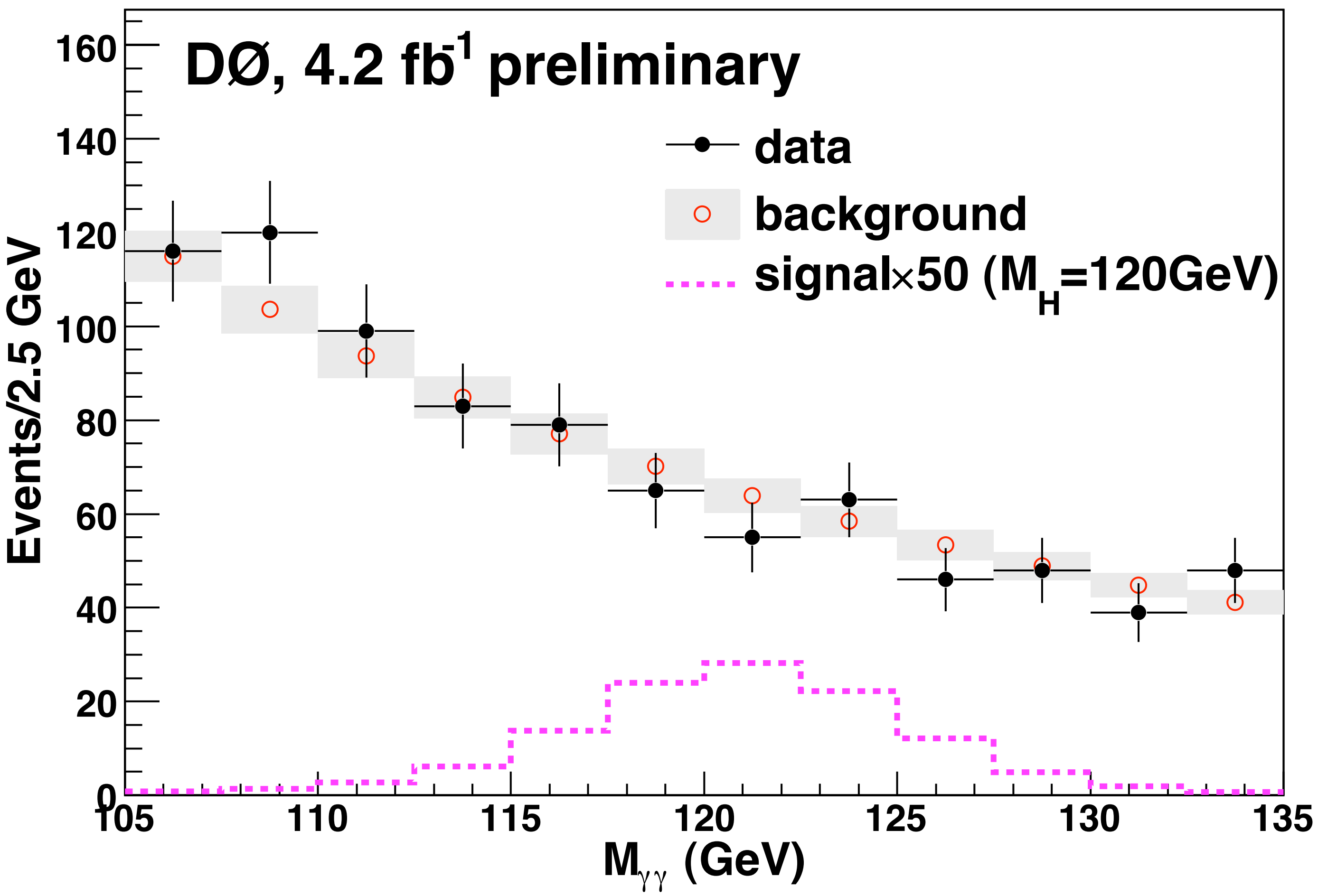
$ZH \rightarrow \nu\bar{\nu}b\bar{b}$





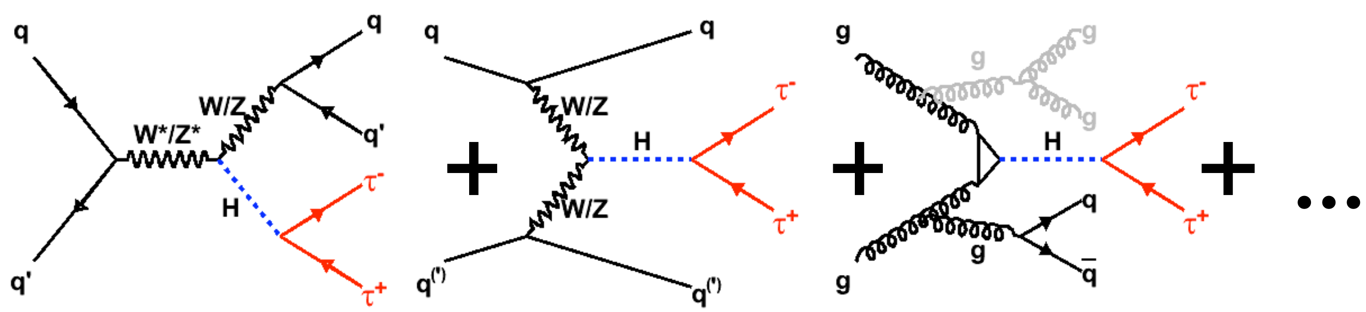
- D0 uses boosted decision trees
- D0 expects 8.4 x SM cross section, observes 7.5 x SM for m_H=115 GeV hypothesis
- CDF uses neural network
- CDF expects 5.6 x SM expected and 6.9 x SM observed

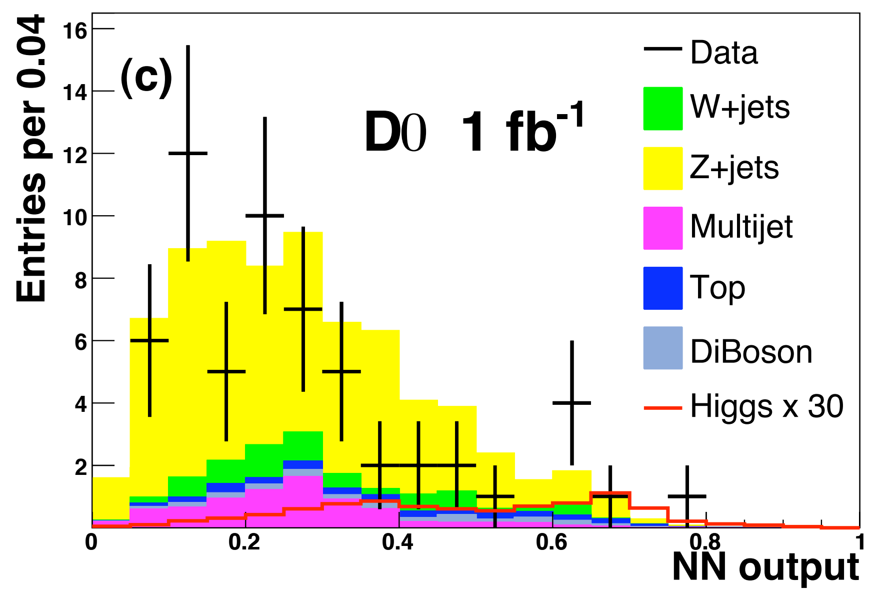
$H \to \gamma\gamma$

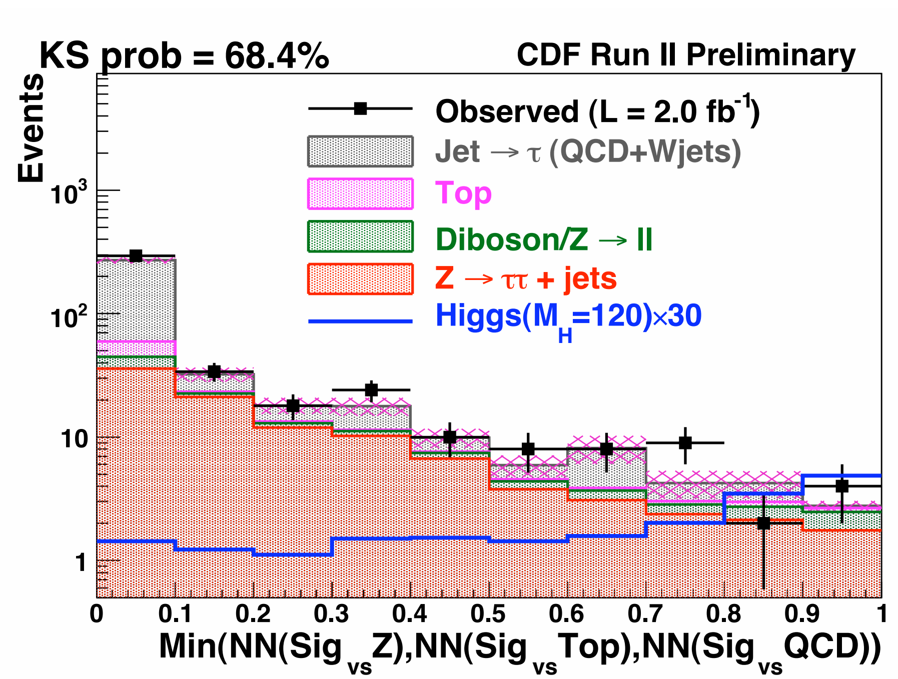


- D0 searched for Higgs decaying to photons via a loop
- By modelling the QCD + 2 photons background using data
- Look in a sliding mass window of 15 GeV for bump
- (Also used to set limits on BSM Higgs.)
- No excess diphotons seen
- Expected limit of 18 x SM cross section, observed 13 x SM

$$H + X \rightarrow \tau^{+}\tau^{-} + X$$

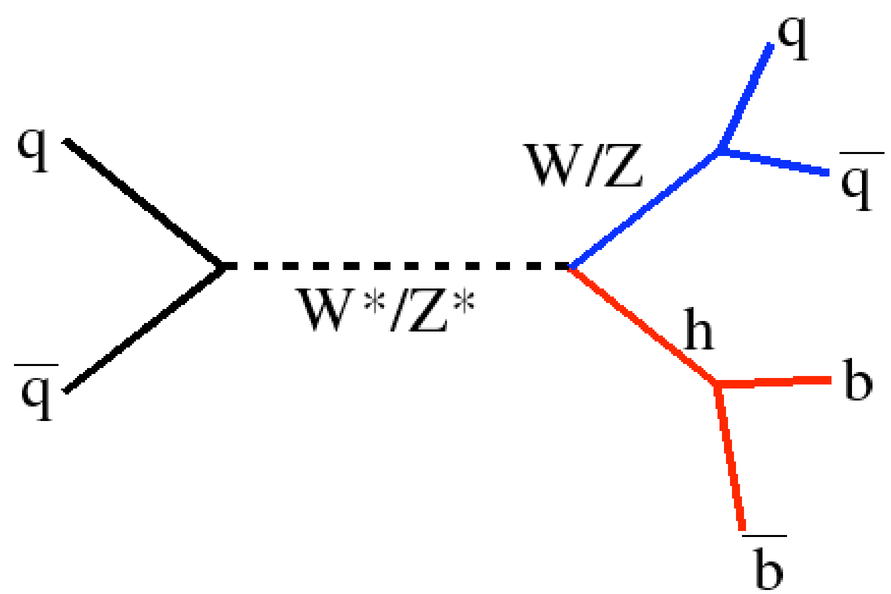


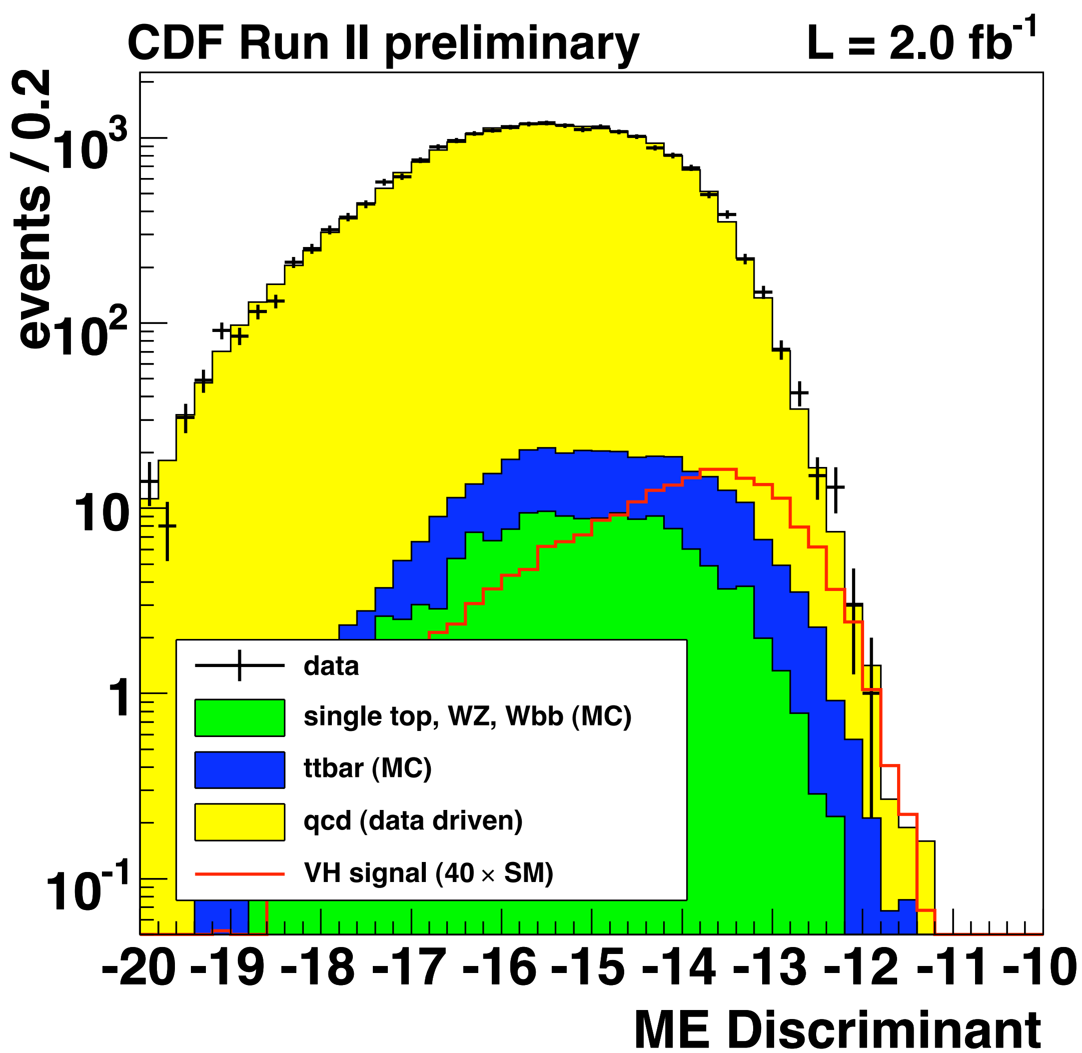




- Both experiments look for inclusive Higgs to tau decays
- Difficult search to perform
- D0 expects a limit of 28 x SM cross section and observes a limit of 27 x SM
- CDF expects 25 x SM, observes 31 x SM

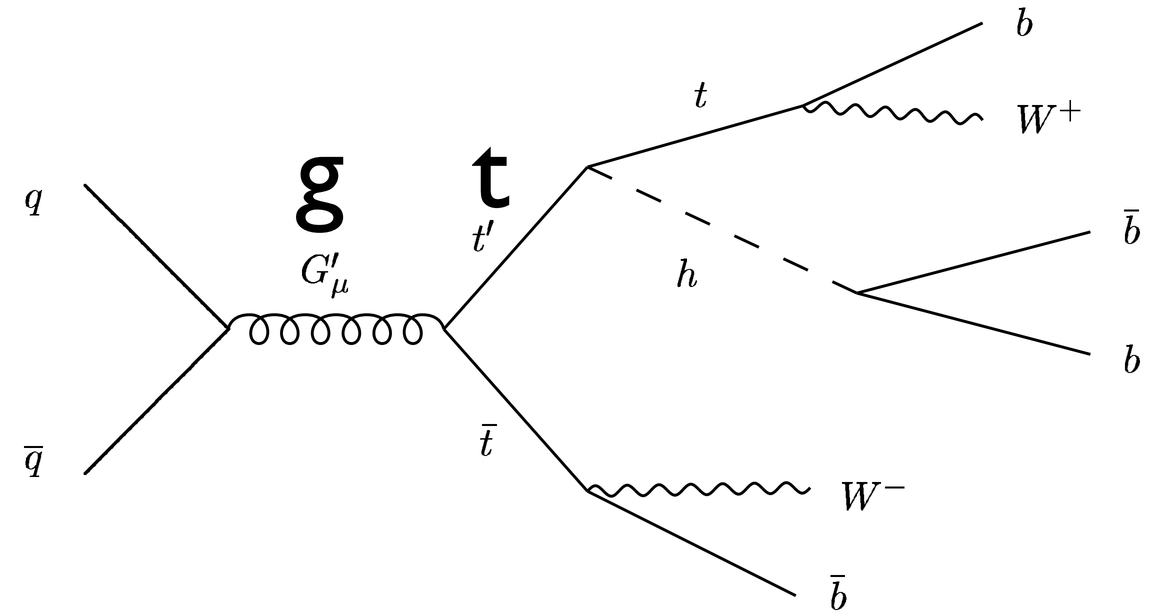
$W/Z + H \rightarrow qqbb$



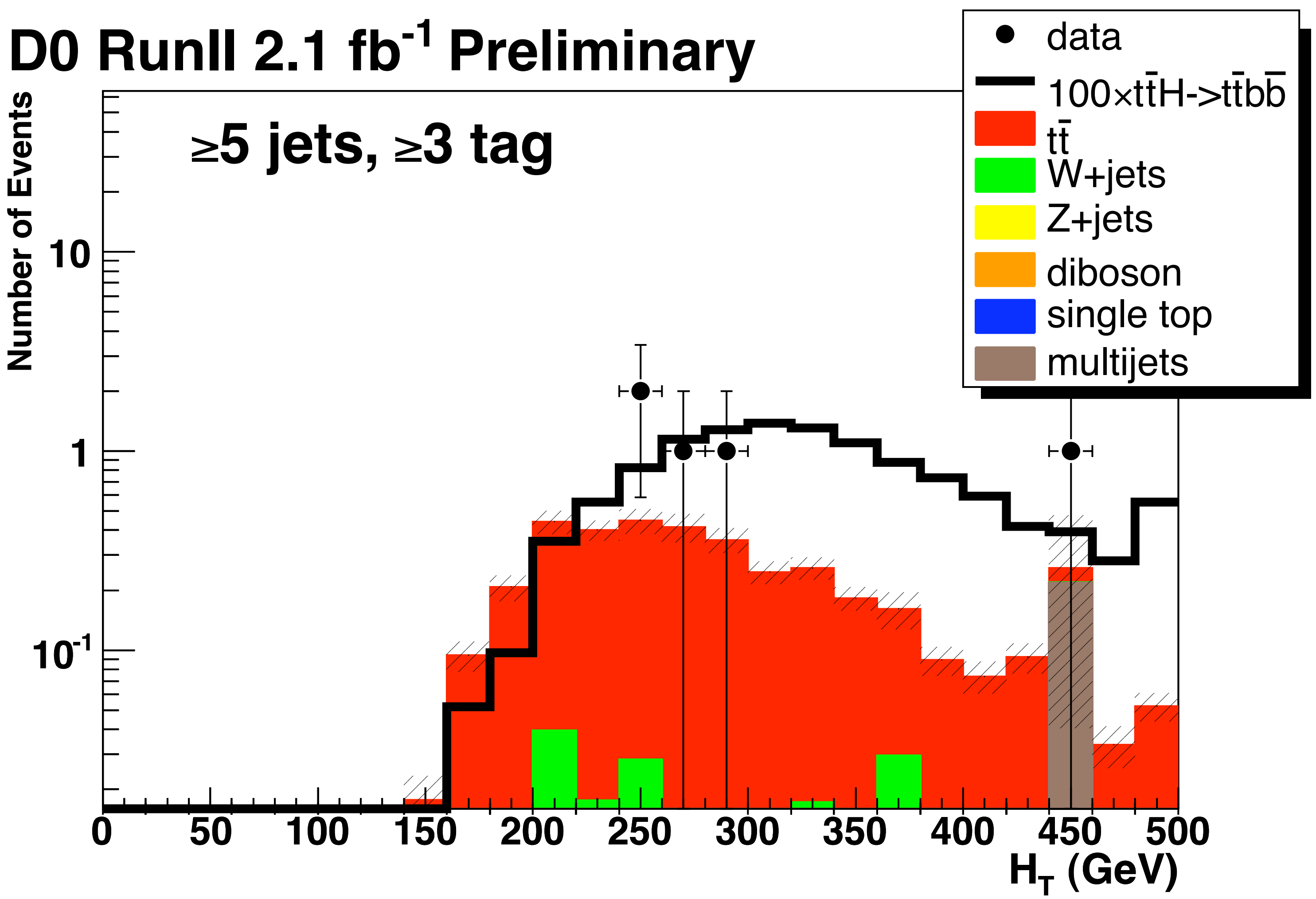


- CDF searched for Higgs in fully hadronic final state produced in association with a massive vector boson
- They used tree-level matrix elements to categorize the likelihood of an event coming from signal or a background process
- QCD background dominates, but also have top and WZ, Wbb
- They expected a limit of 37 x SM cross section, observed 38 x SM

$t\bar{t}H \rightarrow t\bar{t}b\bar{b}$



- D0 searched for Higgs produced by a top radiation
- This channel is also sensitive to BSM enhancements from a t'



- Lots of b-jets in final state
- Exploit the kinematic differences between ttbar and ttH
- Expected a limit of 45 x SM cross section, observed 64 x SM for m_H=115 GeV hypothesis

“High Mass” Searches

- In mass region where $H \rightarrow W^+W^-$ dominates, we look in production modes where the Higgs is made via gluon fusion in a top loop. This is the largest production mode.

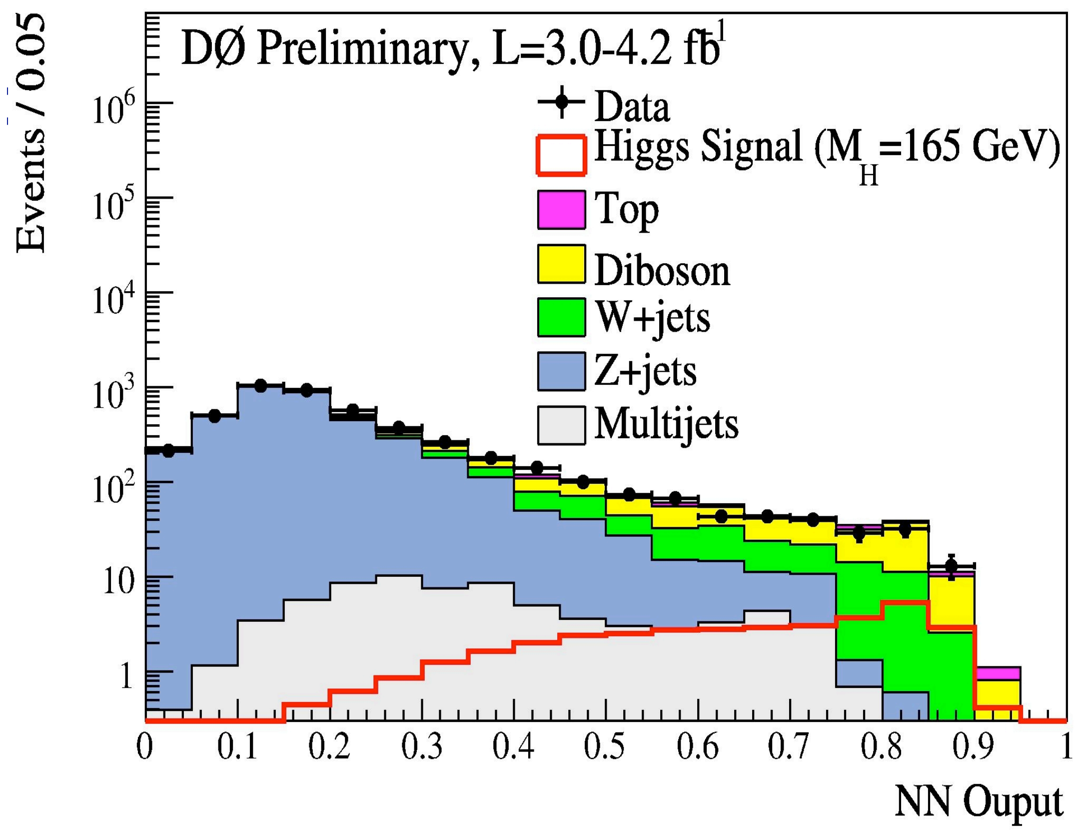
- Higgs decays into W’s. We use the clean signatures where the W’s decay into leptons. This is easiest way to trigger and reconstruct these events

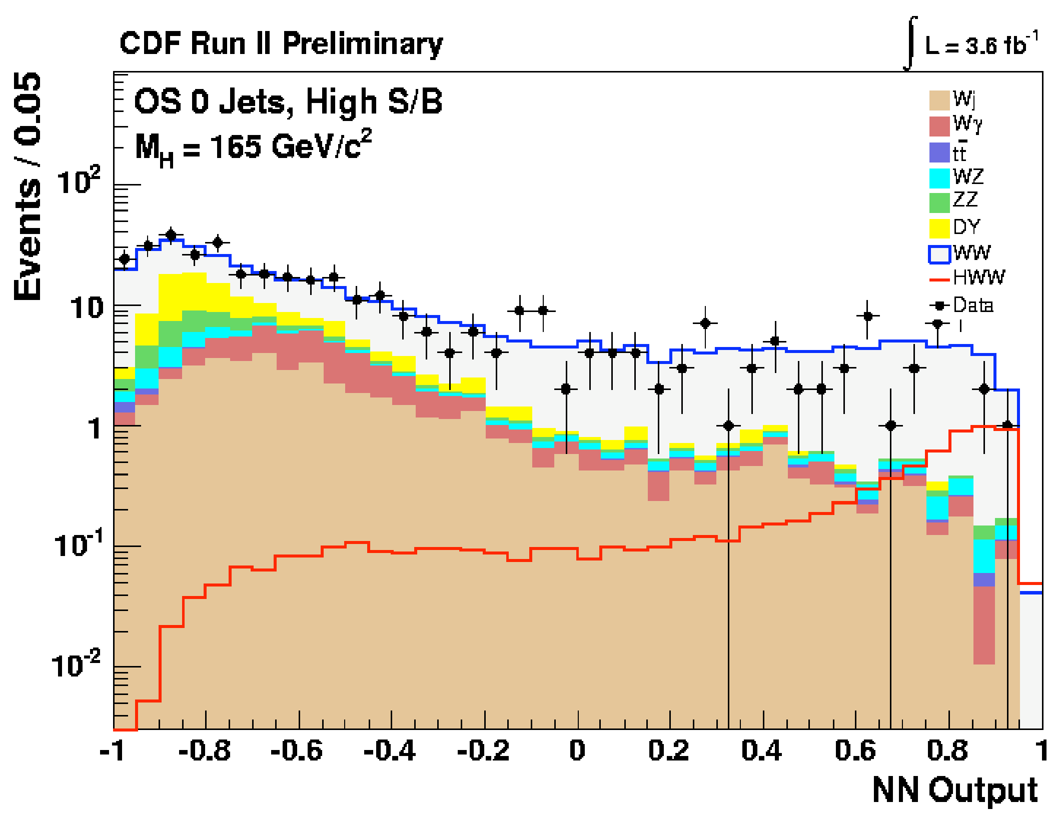
- Even though the (cross section x Br) is smaller for this mass region compared to the “low mass” searches, it turns out to be our most sensitive search and has given the Tevatron our 1st limit on SM Higgs

$$gg \to H \to W^+ W^- \to \ell^+ \nu \ell^- \bar{\nu}$$

- Signature is two high pT, oppositely signed charged leptons (e and μ), missing energy, angular correlation of leptons from spin correlation ($\Delta\phi_{lep}$ is a good discriminator)
- Also sensitive to leptonic tau decay modes
- Backgrounds from leptonic Z/γ^* decays, top, diboson and W+jets & QCD where jets fake leptons
  - CDF: 0, 1, or 2 jets; pT_{lep} > 20, 10 GeV and opp. sign; M_{ll} > 16 GeV; MET along lepton direction > 25 GeV for ee, μμ; MET > 15 GeV for eμ
  - D0: $pT_{\mu,e}$ > 10,15 GeV and opp. sign; M_{ll} > 15 GeV; (in μμ, N_{jet}<2, $\Delta R_{\mu,jet}$>0.1, pT_{μ}>15 GeV); MET > 20 GeV; $\Delta\phi_{lep}$<2 and <2.5 for μμ. (Also some cleanup other cuts.)

$$gg \to H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$$

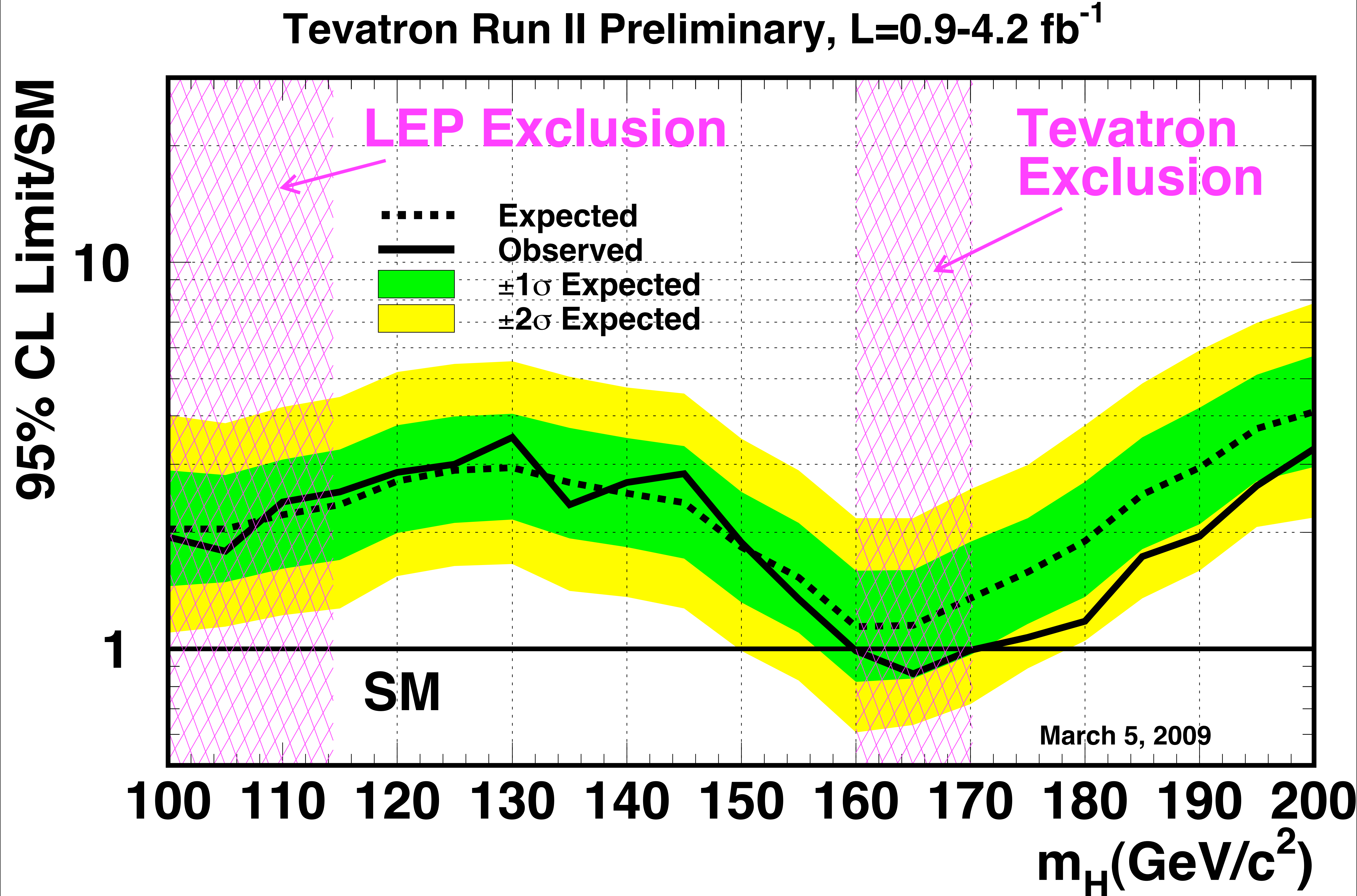




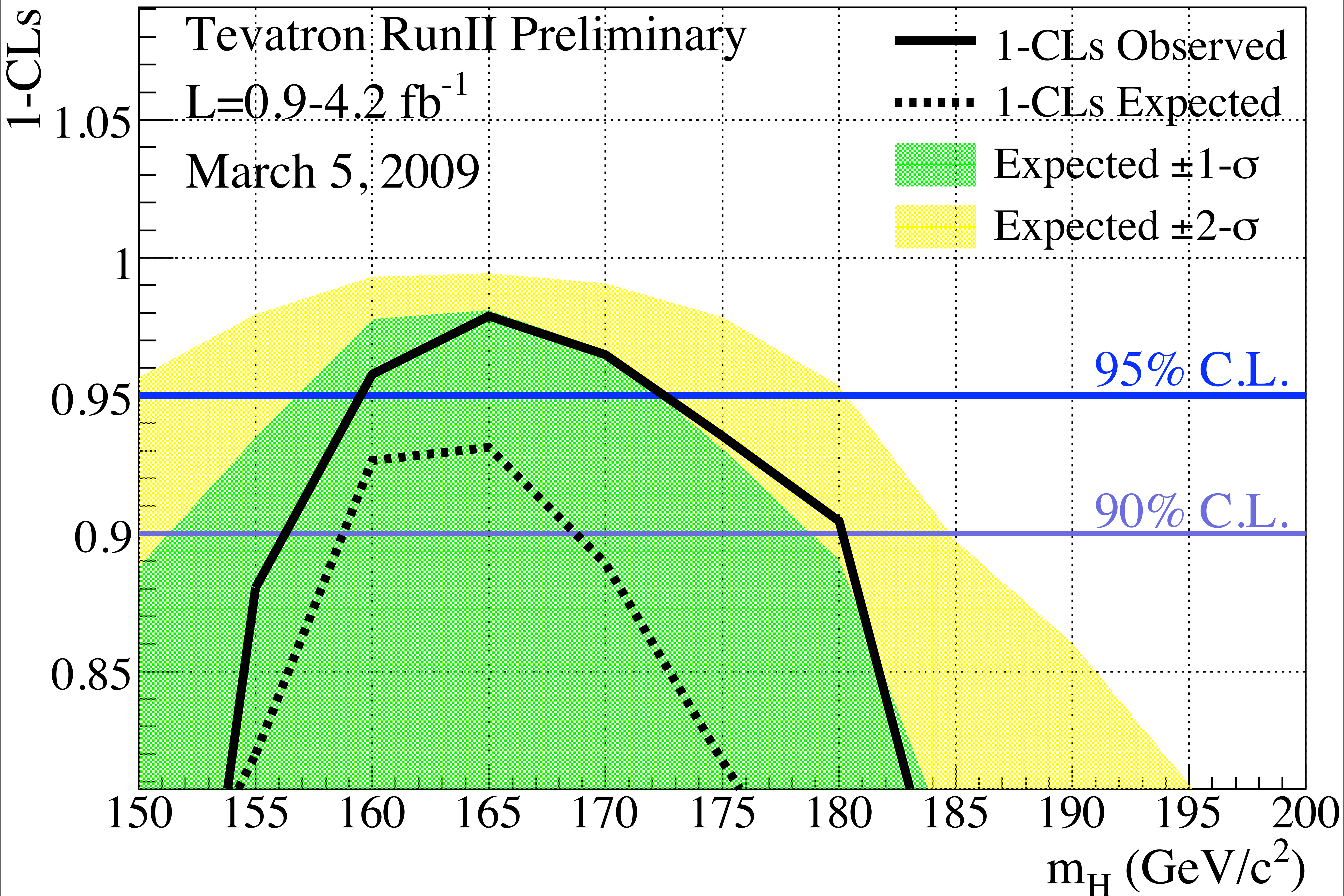
- Both D0 and CDF use neural nets to distinguish kinematic differences between signal and background
- D0 expected a limit of 1.7 x SM cross section, observed 1.3 x SM for m_H=165 GeV hypothesis
- CDF expected 1.5 x SM (including HW to WWW mode), observed 1.3 x SM. This was done in 0, 1, 2 jet analyses

D0 + CDF SM Higgs Combination

- In the same spirit as the LEP Higgs working group, which combined the search results of L3, Opal, Delphi and Aleph, into a LEP-wide global Higgs search, the Tevatron Higgs working group has done something similar. (Both Bayesian and CL_s techniques used.)
- This is a very detail-oriented piece of work that combines something like over 70 different independent channels.
- Use full histogram of "final distribution" of each search channel to take advantage of full shape information
- Accounting for systematic errors is non-trivial!



SM Higgs excluded between 160 < m_H < 170 GeV at 95% CL


Tevatron RunII Preliminary
L=0.9-4.2 fb-1
March 5, 2009
1-CLs Observed
1-CLs Expected
Expected ±1-σ
Expected ±2-σ
95% C.L.
90% C.L.
1-CLs
1.05
1
0.95
0.9
0.85
150
155
160
165
170
175
180
185
190
195
200
m_H (GeV/c^2)

Beyond the Standard Model

- Since we've never directly observed a Higgs particle, it's still possible that if it exists, things are more complicated than what the Standard Model predicts.

- In the Minimal Supersymmetric Standard Model, we have two neutral Higgs bosons (h, H), one psuedoscalar (A), and a charged pair of Higges ($H^{\pm}$)

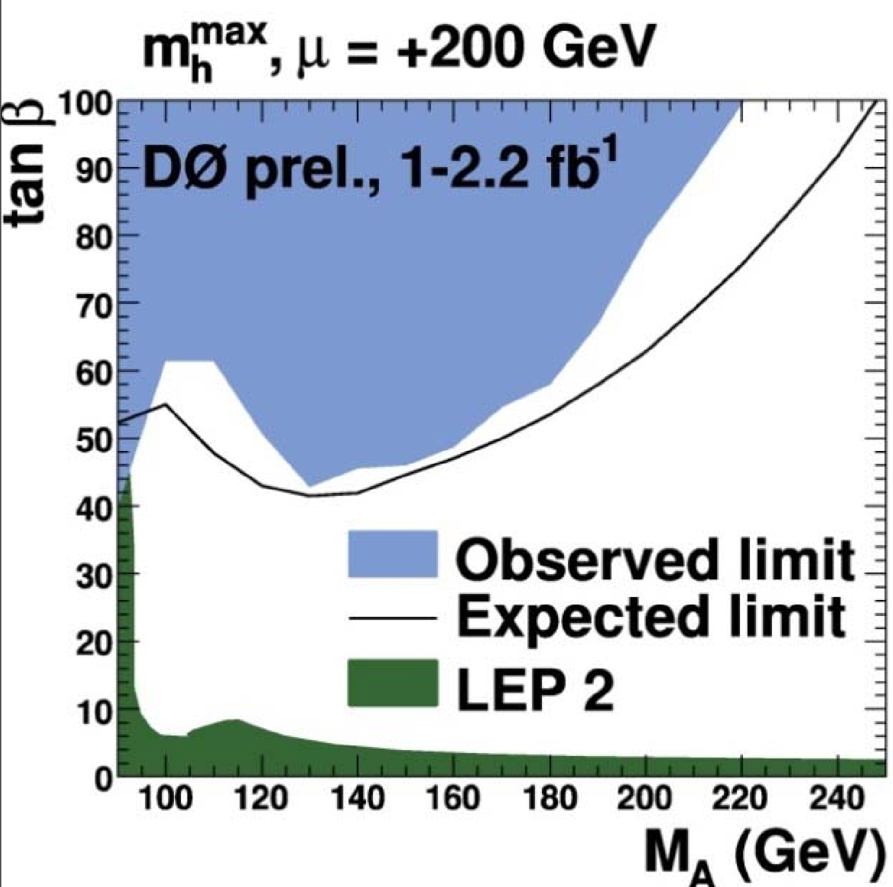
- At tree-level (which is not a good approximation in the MSSM), the Higgs sector is a function of the ratio of the VEV's (tanβ) and m_A

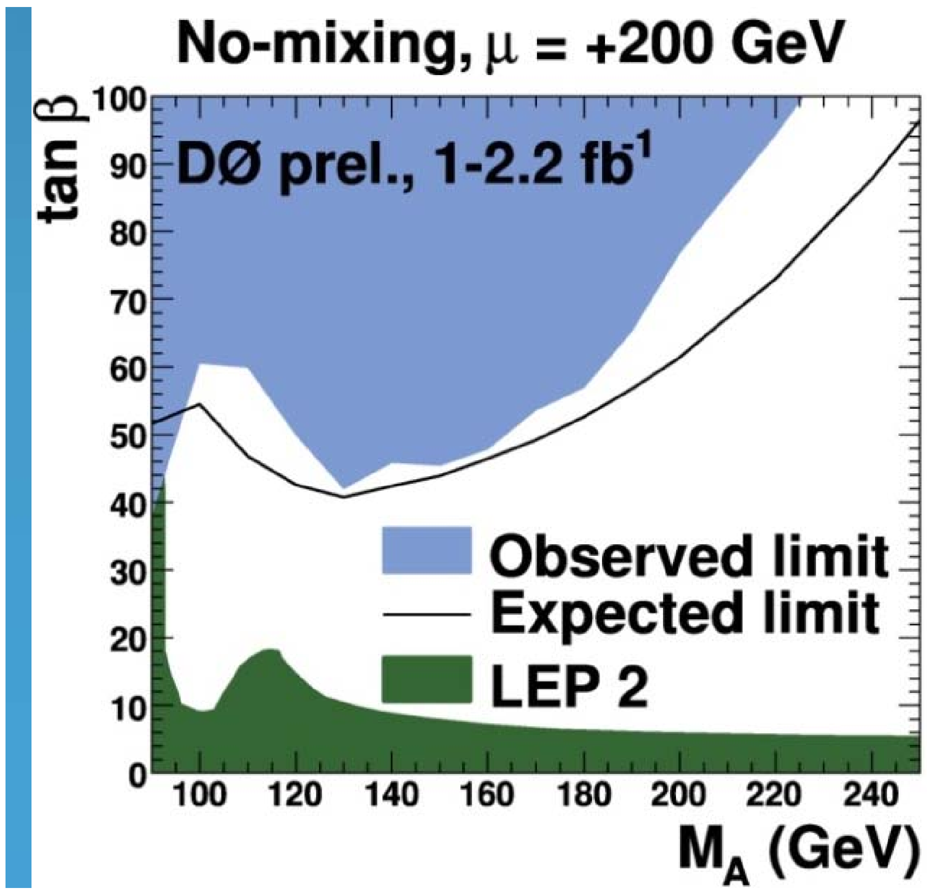
- We also consider other BSM models (fermiophobic, generic charged Higgs: no time to talk about today)

The MSSM Higgs

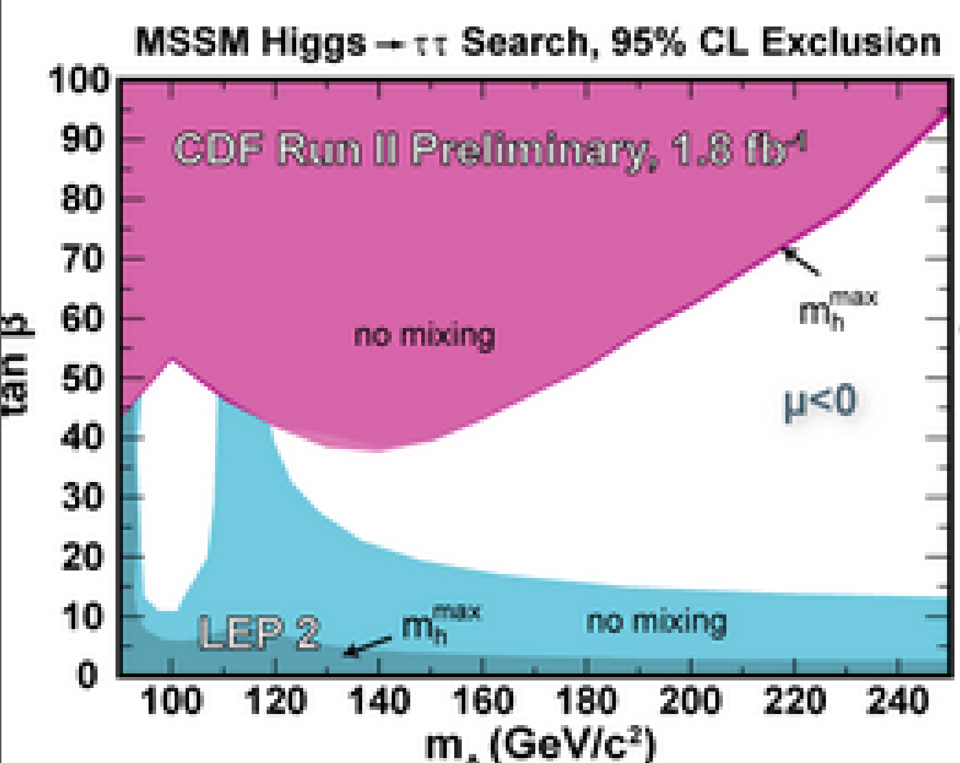
- Higher order corrections are important in the MSSM and other parameters affect the Higgs sector and influence Higgs production cross sections and decay modes
- The community has come up with groups of "standard" sets of SUSY parameters to report our Higgs search results in. They're supposed to bracket various scenarios, but it's still somewhat complicated
- At high tanβ, vertices with b quarks grow like $\tan^2\beta$. Because of g-fusion with a b loop at the Tevatron, this makes MSSM Higgs searches complimentary in sensitivity to what we did at LEP: we now access parameter space that wasn't possible in e^+e^-

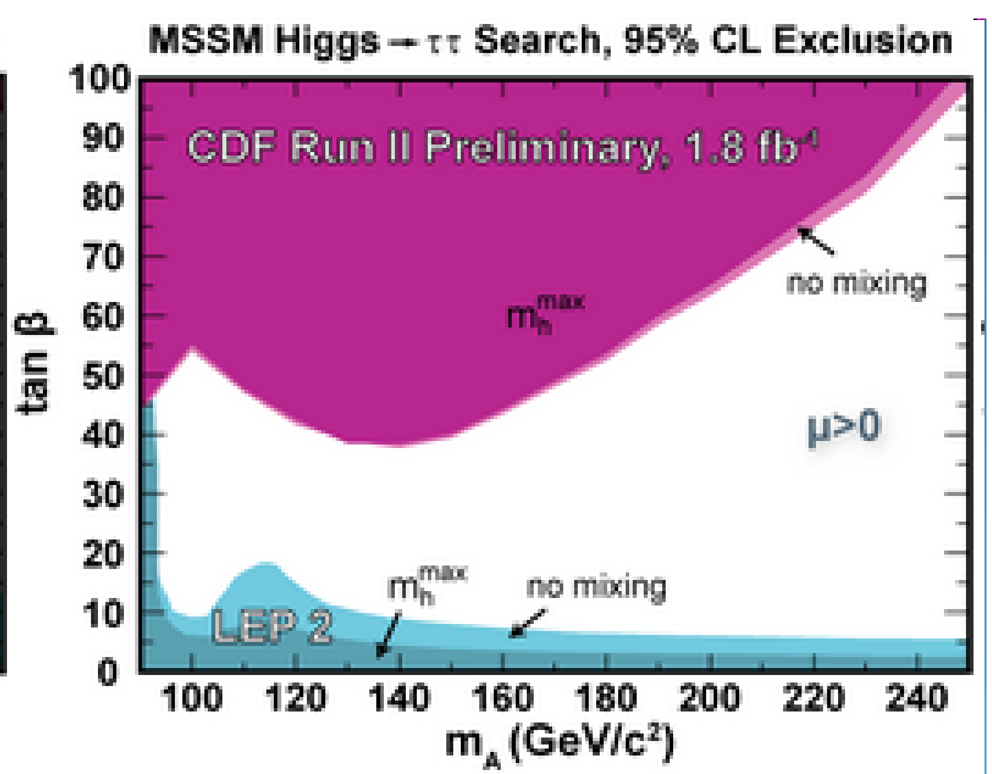
MSSM Higgs to $\tau^+ \tau^-$





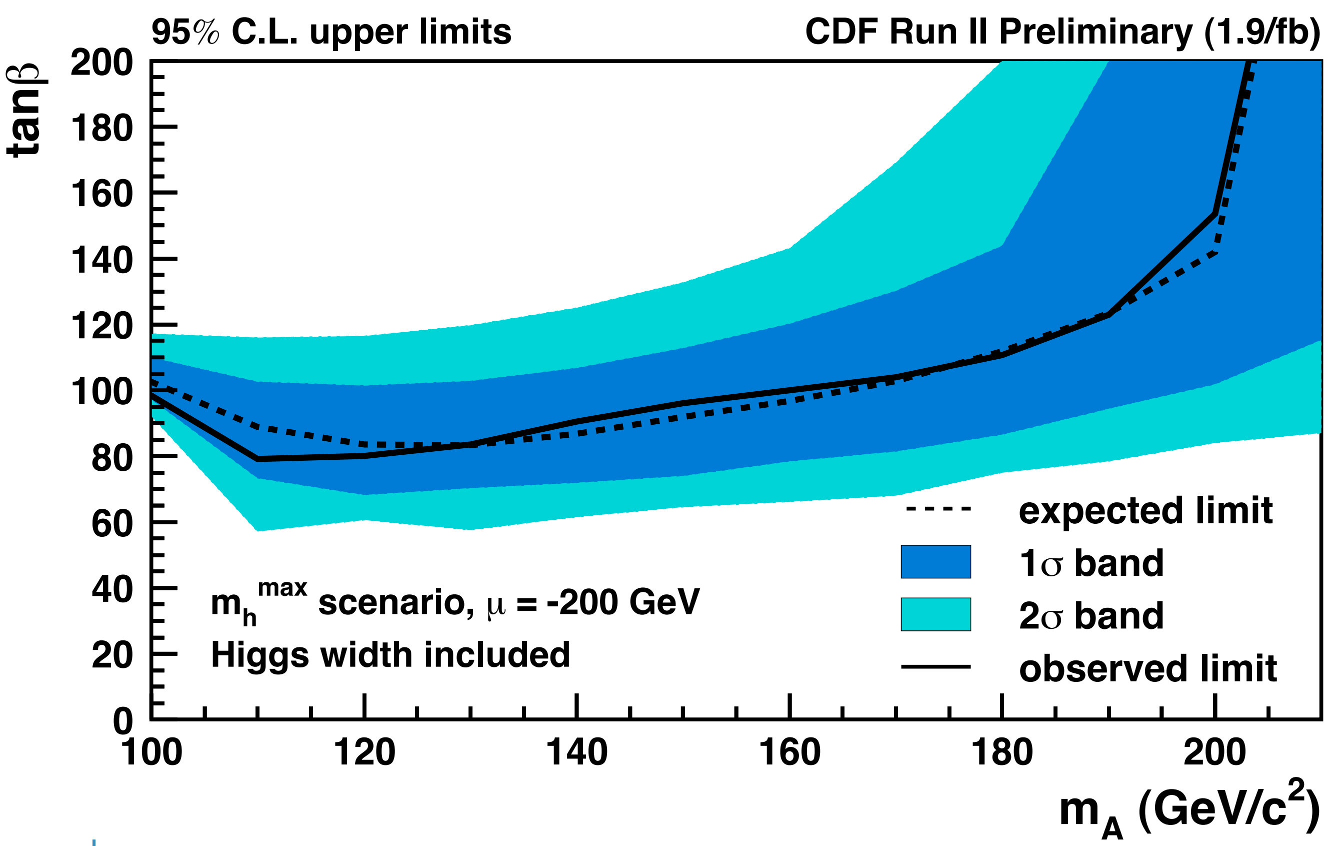
- D0 looks for inclusive tau tau events with at least one leptonic decay
- Use $M(\tau_1, \tau_2, MET)$ for final variable

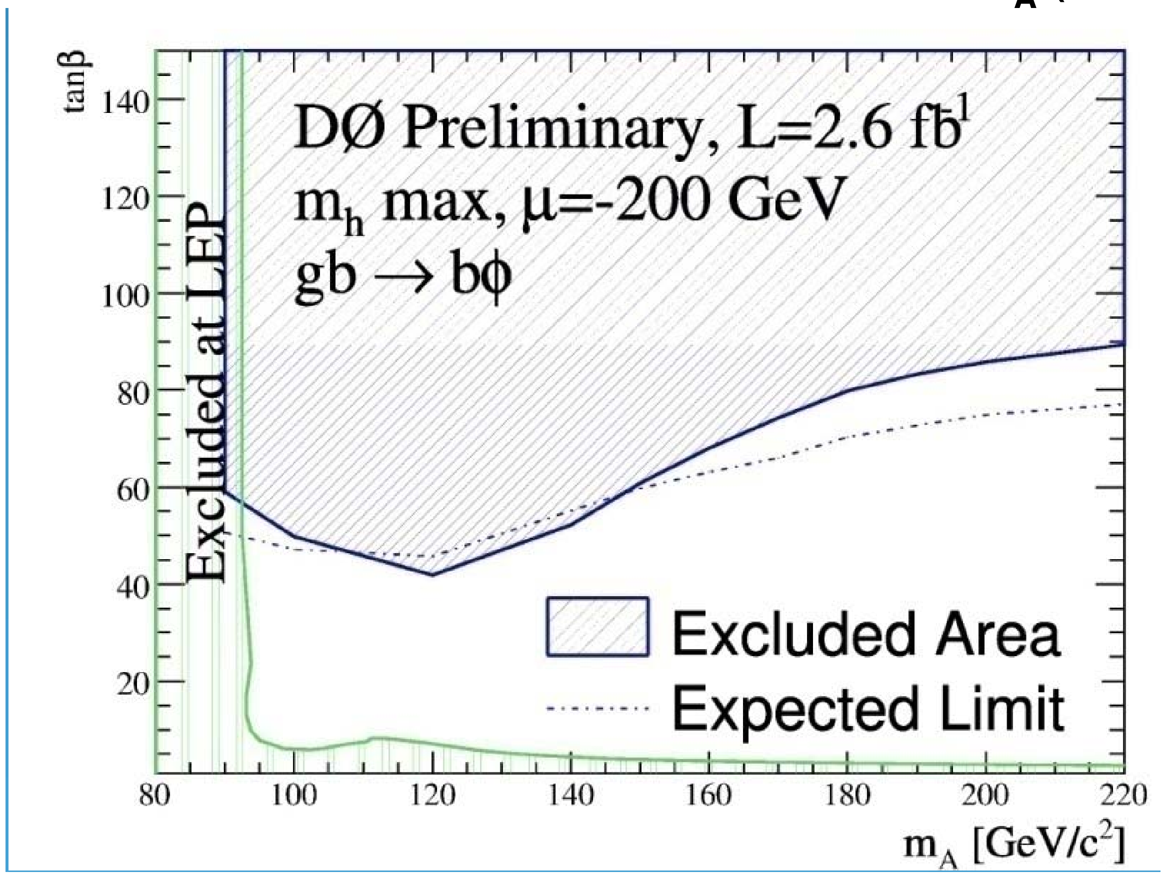




- CDF has a hadronic tau trigger & good hadronic tau reco
- Use $M(\tau_1, \tau_2)$ for final variable

MSSM Higgs to bb



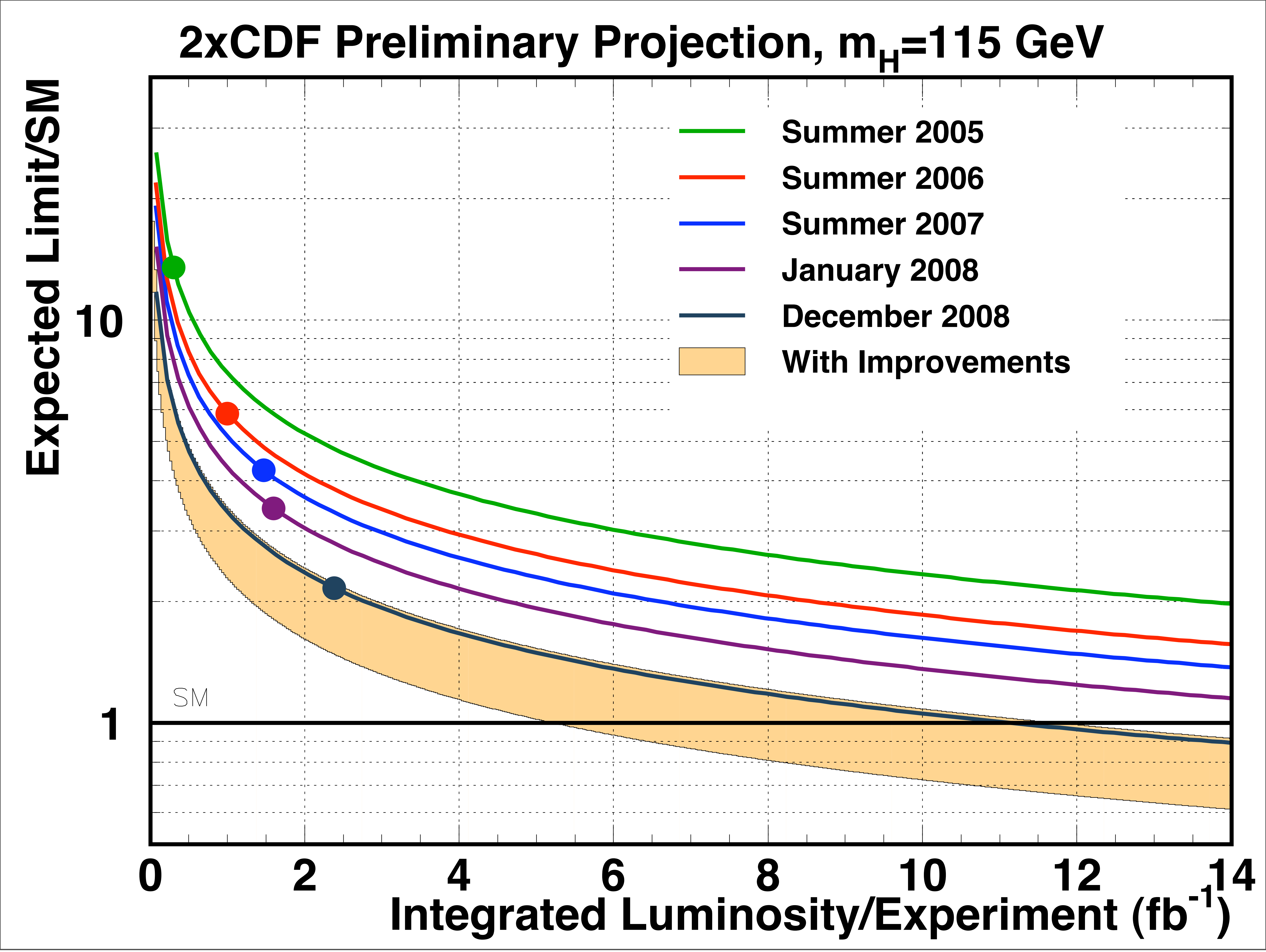


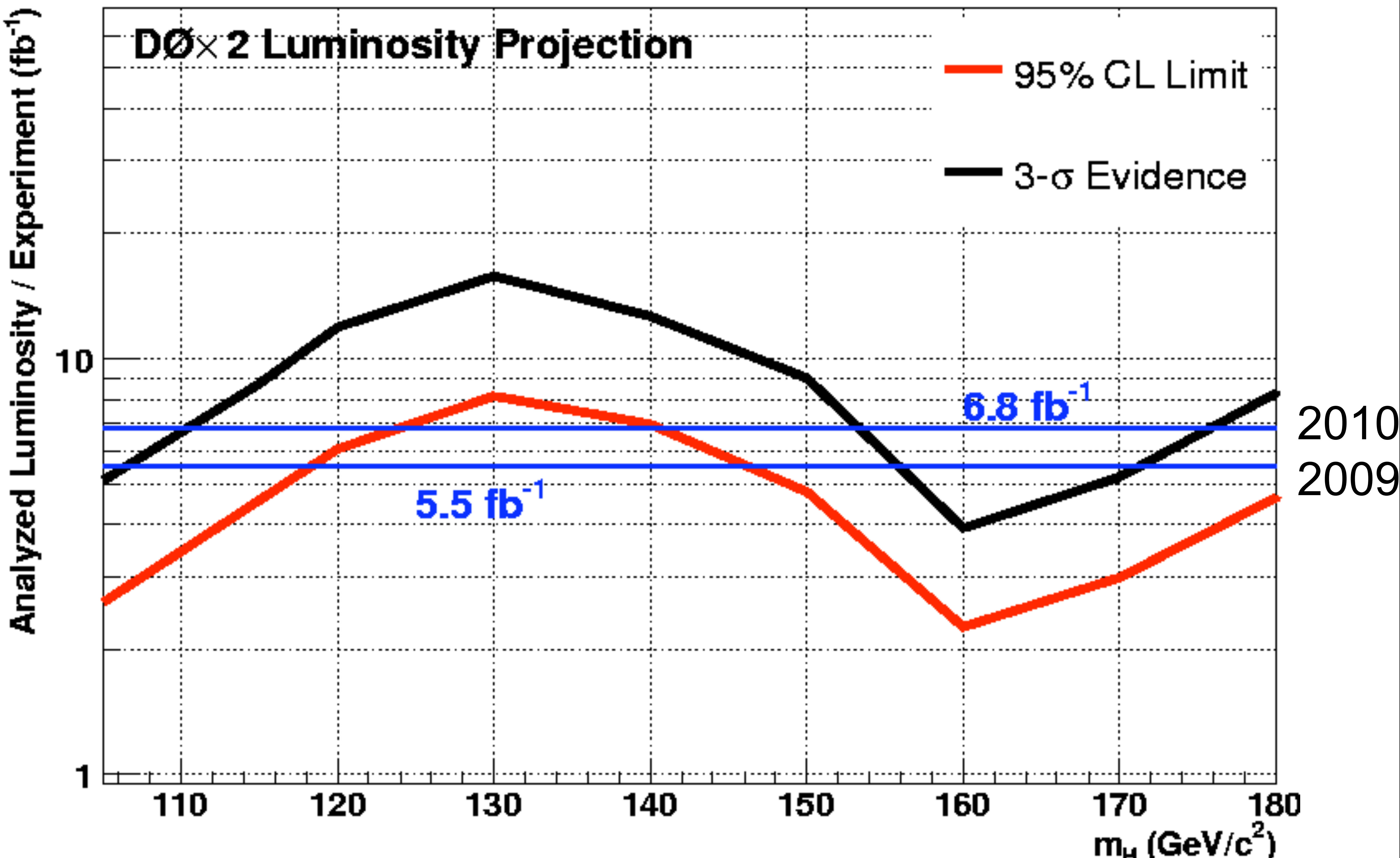
- Both experiments also look for MSSM Higgs decays into b quarks in the production mode where the Higgs comes with associated b quarks
- 3-4 b's in fully hadronic final state: b-tagging very important
- High values of tanβ are now ruled out in the MSSM for all values of m_A

Summary

- The Tevatron accelerator is performing very well
- CDF and D0 have continue to do a very thorough search for the Higgs, even in these days of limited manpower as the LHC comes online
- We've set the first direct 95% CL limits on the standard model Higgs
- Expect continued improvement and reach

Backup Slides


2xCDF Preliminary Projection, m_H=115 GeV
Expected Limit/SM
Integrated Luminosity/Experiment (fb^{-1})
Summer 2005
Summer 2006
Summer 2007
January 2008
December 2008
With Improvements
SM
1
10
0
2
4
6
8
10
12
14


DØ× 2 Luminosity Projection
95% CL Limit
3-σ Evidence
6.8 fb-1
5.5 fb-1
2010
2009
Analyzed Luminosity / Experiment (fb-1)
10
1
110
120
130
140
150
160
170
180
mH (GeV/c2)